Use of recycled construction and demolition wastes as aggregates in pre-cast block works

by

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Declaration

I hereby declare that this thesis is my own work and that, to the best of my knowledge and belief, it reproduces no material previously published or written, nor material that has been accepted for award of any other degree or diploma, except where due acknowledgement has been made in the text.

Lam Chi Sing

Abstract

As landfill space in Hong Kong is running out, the high waste generation rate in the territory becomes a major concern. In 2004, there was about 17,500 tonnes of waste required to be landfilled per day and about 40% of this waste was construction and demolition (C&D) waste. To reduce the waste quantity, government has implemented a charging scheme on C&D waste at the end of 2005. The purpose of this policy is to encourage contractors to reduce, reuse and recycle C&D waste. In fact, reuse of C&D waste is very common in other countries. C&D waste can be used as an aggregate replacement in concrete, sub base and masonry products. Although the high water absorption and porosity of recycled aggregates derived from C&D waste would affect the quality of concrete, there have been many studies which showed that the use of recycled aggregate in nonstructural concrete is feasible. Recycled aggregates can also be used in structural concrete by applying special mixing curing and casting methods. In masonry applications, although a number of studies have shown that it is feasible to produce paving and partition blocks by using recycled aggregates, there is a need to further understand the factors affecting the engineering properties of the masonry and paving products produced in order to optimize the production.

This study aims to develop a set of scientific design principle and guidelines to optimize

the performance of pre-cast masonry and paving products produced with recycled aggregates. The parameters studied included the effect of aggregates to cement (A/C) ratio, grading of the aggregates and aggregate properties on the properties of the blocks. The study was conducted by carrying out a series of experiments using different A/C ratios, types and grading to understand their effects on the properties of the blocks.

The study results showed that strength of the blocks prepared with different aggregates increased with the decrease in A/C ratio, and water absorption and abrasive resistance of the blocks were also improved when the A/C ratio decreased.

The study results also showed the grading of the aggregates significantly affected the performance of the blocks. Models based on ideal grading curve, fineness modulus and packing density were used in the study to optimize the grading requirements of aggregates for masonry and paving block applications.

To determine the effect of aggregate types and properties, different types of aggregates (recycled crushed glass, recycled crushed aggregate and natural crushed aggregate) were used in the experiments. The result indicated that the 28th day compressive strength would increase when the recycled aggregate was replaced by natural crushed aggregate but decrease when the recycled aggregate was replaced by recycled crushed glass. Although the use of recycled crushed glass would reduce the strength, it could nevertheless compensate the high water absorption of the recycled aggregate and thus reduced the overall water absorption of the blocks making a better product.

However, alkali silica reaction (ASR) became a concern when glass was used in the cementitious system. A series of accelerated mortar bar tests were carried out to determined the level of ASR expansion. It was found that by using appropriate mix proportioning and addition of PFA, the expansion caused by ASR reaction could be effectively suppressed.

With the assistance of a local block manufacturer, the optimized mix proportions developed in the laboratory was used at a few plant trials. The plant trials results confirmed that it was feasible to produce quality pre-cast masonry and paving blocks (meet Grade A standard) by using recycled aggregates.

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Chapter 1 Introduction

1.1 Background:

In recent years, the disposal of construction and demolition waste (C&DW) in the landfill sites of Hong Kong has significantly increased due to the running out of reclamation areas. According to the data of the Hong Kong Environmental Protection Department (EPD) [2004a], the C&DW formed a large part of the total waste disposed of in landfills (48% of total waste in 2004). However, the landfills will be filled up in 6 to 10 years and public fill capacity will be run out by mid 2006. Therefore, the Hong Kong government has commenced a charging scheme at the end of 2005 to reduce the C&DW generation and to encourage the recycling C&D waste. At the same time, a lot of interests has been invested on the research on the feasibility of using the C&DW to improve the recycling technique in Hong Kong. One of the feasible approaches is to use the C&DW in concrete blocks. Several trial had been conducted and tested for more than a year and the performance of the paving blocks was satisfactory. To encourage the use of these paving blocks, the Hong Kong government published a document, Environment, Transport and Works Bureau Technical Circular (ETWB) [2004], to encourage more contractors to use these paving blocks in government projects. The document also give a clear specification for the paving blocks. Although paving blocks prepared with C&DW was able to achieve Grade B requirements, of the specification most of them were not able to achieved Grade A requirements due to the high water absorption characteristics of the C&DW. Also, there is almost no design guide for concrete blocks prepared with recycled aggregate.

1.2 Objectives

The principal objective of this project was to optimize the use of waste materials for concrete blocks production.

Factors which would affect the performance of the blocks were considered and as a result the following additional objectives were identified:

- Investigate the relationship between the A/C ratio and concrete block properties.
- Investigate the relationship between the aggregate properties and concrete block properties.
- Investigate the relationship between the aggregate grading and concrete block properties.
- Investigate the durability of the concrete blocks when used for construction purposes.
- Optimize the mix proportion of concrete block produced with recycled

materials.

1.3 Scope of works

The following tasks were carried out in order to fulfill the objectives of this project:

- The research commenced with a literature review, followed by a comprehensive experimental programme.
- Concrete blocks were prepared with different A/C ratio.
- Concrete blocks were prepared with different aggregates.
- Concrete blocks prepared with different gradings.
- Mortar bars were prepared for the durability test.

1.4 Organisation of thesis

This thesis is divided into nine chapters. The first Chapter covers the background, objectives and scope of this project. A brief literature review is given in Chapter two. Chapter three contains details of the materials and methods used in this project. The analytical results obtained are presented and discussed in Chapters four to eight. Chapter four focuses on how the aggregate to cement (A/C) ratio and aggregate type would affect the concrete block properties. Chapter five concentrates on the effect of aggregate grading on the block properties. Chapter six looks at the effect of PFA on the durability of blocks prepared with recycled crushed glass (RCG). Chapter seven further investigates the effect of PFA on the prepared block's engineering properties. In Chapter eight, factory and laboratory prepared samples were compared and a draft design guide is recommended. Chapter nine concludes the findings of the research.

Chapter 2 Literature Review

2.1 Definitions of construction and demolition materials (C&DW)

The U.S. Environment Protection agency [2005] defines Construction and demolition (C&D) material as debris which consists of the materials generated during the construction, renovation, and demolition of buildings, roads, and bridges. C&D debris often contain bulky and heavy materials such as

- concrete,
- wood (from buildings),
- asphalt (from roads and roofing shingles),
- gypsum (the main component of drywall),
- metals,
- bricks,
- glass,
- plastics,
- salvaged building components (doors, windows, and plumbing fixtures), and
- trees, stumps, earth, and rock from clearing sites.

2.2 Local situation

Up until 2004 the construction industry has been the major solid waste generator in Hong Kong (48% of total waste in landfills) [EPD, 2004]. The extensive building and infrastructure development projects as well as redevelopment of old districts have led to an increase in C&DW generation in the last decade. This has caused the disposal of the wastes to become a severe social and environmental problem in the territory. Up to present this problem has often been dealt with by disposing of at landfills and public filling areas locally.

According to the Hong Kong Civil Engineering and Development Department (CEDD) [2004] 20.5millon tonnes of C&DW was generated per year. Of this amount [EPD, 2004], over 80 % were inert materials. The remaining proportion represented less than 20 % of the total C&D materials generated in 2004, these were non-inert materials. C&DW has been taking up valuable landfill space, on this trend Hong Kong landfill space will run out within 7 to 11 years.

Hong Kong is also running out of public filling areas, which has traditionally been used to accommodate the large amount of inert granular materials generated from excavation & demolition. In recent years, public concerns and objections have often delayed, reduced the scale of or stopped the implementation of planned reclamation projects (particularly those within the Victoria Harbour). As a result there will be no further new reclamation projects. Hence the shortage problem for landfill space will be aggravated and means there are a lot of interests to recycle the material.

2.3 Recycling of C&DW globally and recycled aggregate specifications

In Europe the recycling of building materials first started near the end of World War II when bricks and other materials recovered from the ruins of war were utilized for reconstruction of amenities [Olorunsogo, 1999]. Similarly inert materials from C&DW can be sorted and crushed to provide recycled aggregates for construction applications. According to the European commission [2000] working document, more than 450 million tons per year of construction and demolition waste (C&DW) was generated within the European Union, About 70% of C&DW was disposed to landfills. However, amongst the member states, Demark, the Netherlands and Belgium have all been able to achieve a C&DW recycling/reusing rate higher than 80%. Their success in recycling and reusing C&DW can be attributed to their government policy and shortage of natural resources. On the other hand, the high quality of recycled aggregate produced has meant that countries in Europe, Japan and United States have all modified their specifications to adapt with the growing trend of using recycled aggregate in construction works. There are several well-known specifications as shown below:

RILEM [1994] has designed a specification for concrete with recycled coarse aggregates (>4mm). They suggested a classification to the recycled aggregates according to their ingredients and specified properties. Maximum allowable strengths of concrete prepared with different classes of recycled coarse aggregates are:

Table 2.3.1 Specification of recycled concrete aggregates in concrete from RILEM

Mandatory requirements	RCAC Type I	RCAC Type II	RCAC Type III	Test method
Min. dry particles density (kgm^{-3})	1500	2000	2400	ISO6783&7033
Max. water absorption (% m/m)	20	10	3	ISO6783&7033
Max. content of material with SSD<2200kgm^{-3}(% m/m)	-	10	10	ASTM C123
Max. content of material with SSD<1800kgm^{-3} (% m/m)	10	1	1	ASTM C123
Max. content of material with SSD<1000kgm^{-3} (% m/m)	1	0.5	0.5	ASTM C123
Max. content of foreign materials (metals, glass, soft material, bitumen) (% m/m)	5	1	1	Visual
Max. content of metal (% m/m)	1	1	1	Visual
Max. content of organic material (% m/m)	1	0.5	0.5	NEN 5933
Max. content of filler (<0.063mm) (% m/m)	3	2	2	prEN 933-1
Max. content of sand (% m/m)	5	5	5	prEN 933-1
Max. content of sulfate (% m/m)	1	1	1	BS 812, part 118
Max. allowable strength class	C16/20	C50/60	No limit	

In Australia, CSIRO [1998] classified clean recycled aggregate as class 1 recycled aggregate: Recycled concrete produced from a quality uniform stock of clean concrete containing no more than 2% of brick, stony material or other forms of contaminants, manufactured for use as coarse aggregate, which fulfills various CSIRO specified properties, in the production of pre-mix concrete having characteristic cube strength up to and including Grade N40 concrete for use in non-structural concrete applications. The recycled aggregate properties are shown in the following table:

Table 2.3.2 Specification of recycled concrete aggregates in concrete from CSIRO

RCA Property	Class 1 RCA	Test method
Particle Density s.s.d (min.)	2100 kgm^{-3}	ASTM 1141.6
Bulk density (min.)	1200 kgm^{-3}	ASTM 1141.4
Water absorption (max.)	6%	ASTM 1141.6
Aggregate Crushing value (max.)	30%	ASTM 1141.21
Total impurity level (max.)	2%	-
LO1 (max.)	5%	-
Lost substance in washing (max)	1%	-
Particle size distribution by	-	ASTM 1141.11

2.4 The application of the recycled aggregates

The use of recycled aggregate has been extensively studied in road construction for sub-base [Cuperus and Boone., 2003]. More recent applications of recycled aggregate include the production of Portland cement concrete and masonry units. Recycled aggregate is often used for road sub-bases and masonry units instead of concrete as the requirements for these tend to be less stringent and also because more research has been carried out to prove the suitability for these applications. The use of recycled aggregate for masonry units, pavement sub-bases and concrete are further reviewed in this chapter.

2.4.1 Pavement sub-base

Pavement is a multi-layers structure, typically composed of either a concrete or an asphalt slab resting on a foundation system. The foundation system consists of various layers such as the base, sub-base, and sub-grade. Conventionally, natural materials such as crushed rocks, selected gravels and stabilized materials are used in road bases. Over the last two decades, research has been undertaken to investigate the possibility of using recycled aggregate in road bases in order to provide a viable option for the use of recycled aggregate.

Chini *et al.* [2001] tested the properties of a road base sample using recycled aggregate produced from a demolished concrete pavement which had a design mix strength of 20 MPa. The sample was tested for gradation, lime rock bearing ratio (LBR), LA abrasion and soundness loss in accordance with AASHTO T 27-93, FM 5-515, AASHTO 96-94 and AASHTO T 104-94, respectively. Test results showed that the road base sample passed all standard requirements of gradation, LBR and LA abrasion with the exception of the soundness test using sodium sulfate. In addition they claimed that the mortar adhered to the recycled aggregate was reactive to sodium sulfate and contributed to an increased loss in the soundness test.

Park [2003] tested the physical and compaction properties of two different recycled aggregates obtained from a housing redevelopment site (RCA-1) and a concrete pavement rehabilitation project (RCA-2). The bulk specific gravity and water absorption values were 2.527 and 2.539 and 1.43 and 1.77 % for RCA-1 and RCA-2, respectively. The optimum moisture contents were 9 % and 12.8 % and the corresponding dry densities were 2.21 and 1.81 Mg/m^3 for RCA-1 and RCA-2, respectively. It was apparent that optimum moisture content increased with an increase in water absorption of the aggregates.

Nataatmadja and Tan [2001] tested the resilient response of a sub-base material made with four different recycled aggregates. The aggregates were originated from concretes with compressive strengths of 15, 18.5, 49 and 75 MPa. The corresponding ten percent fines values were 149, 158, 166 and 187 for the four different recycled aggregates respectively where the ten percent fines values increased with increasing compressive strength of the original concrete. The resilient response of a sub-base material made with recycled aggregate was found to be comparable to that of a sub-base material made with natural aggregate and also to be dependent on the strength of the original concrete, the amount of softer material in the recycled aggregate and the flakiness index.

2.4.2 Concrete

Recycled aggregate has been used as a replacement of the natural aggregate for a number of years. The potential benefits and drawbacks of using recycled aggregate in concrete have been quite extensively studied.

The use of recycled aggregate generally increases the drying shrinkage, creep, and damping capacity and decreases compressive strength, modulus of elasticity of concrete compared to those of natural aggregate concrete [Sri Ravindrarajah and Tam, 1985].

It was found that lower workability was obtained in concrete containing recycled aggregate [Rashwan and Abourisk, 1997 and Dhir *et al.*, 1999]. This phenomenon is mainly attributed to the physical properties of the recycled aggregate's shape and texture and water absorption. The angularity and the rough texture of recycled aggregate create higher internal friction, thus increasing the shear strength capability of concrete and reducing the slump. The high water absorption of the recycled aggregate was further decreased the workability of the fresh concrete.

Hasaba *et al*. [1981] reported that the drying shrinkage of concrete prepared with coarse recycled aggregate and natural sand was 50 % higher than that of conventional concrete. When both coarse and fine recycled aggregates were used, the drying shrinkage of recycled aggregate concrete was as much as 70 % higher than that of conventional concrete. Hansen *et al.* [1985] reported that recycled aggregate concrete had 15 to 30 % lower modulus of elasticity and 40 to 60 % higher shrinkage than those of conventional concrete. Olorunsogo and Padayachee [2002] found that the water sorptivity of concrete prepared with 100 % recycled aggregate was about 39 % higher than that of natural aggregate concrete at the curing age of 28 days. Dhir *et al.* [1999] showed that the compressive strength of concrete with 100 % coarse and 50 % fine recycled aggregates was between 20 – 30 % lower than that of the corresponding natural aggregate concrete. However, the quality of concrete containing recycled aggregate can be improved by using a new technique. Tam *et al.* [2005] reported that a two-stage mixing approach can improve the weak inter-transition zone (ITZ) on the recycled aggregate surface. The two-stage mixing approach can provide better chances for the cement slurry to gel up the recycled aggregate, providing a strong ITZ by filling up the cracks and pores. Poon and Kuo [2004a] reported that one of the most practical ways to utilize a higher percentage of recycled aggregates in concrete is “precasting” with an initial steam curing stage immediately after casting.

On the other hand, Mansur et al. [1999] reported that there was nearly no difference between concretes prepared with granite coarse aggregate and high replacement content of recycled coarse aggregate from high strength clay bricks. Moreover, Tu et al. [2005] applied the Densified Mixture Design Algorithm (DMDA) in the mix design of high performance concrete (HPC)/self compacting concrete (SCC). They used both recycled fine and coarse aggregates to replace natural aggregates. Although, the results showed that slump-loss was large after 1 hour when the HPC was prepared with recycled aggregates and the compressive strength was about 70%-80% of that prepared with natural aggregates, other physical and durability properties satisfied HPC requirements. Therefore, they recommended that recycled aggregates could be used in HPC but a higher design compressive strength was necessary.

2.4.3 Masonry units

The use of recycled aggregates to produce masonry products is still relatively new. An early attempt was made by Collins *et al.* [1998] who used recycled aggregates in the manufacture of blocks for a beam-and-block floor system. The blocks were 440 mm long, 215 mm wide and 100 mm high. Recycled aggregates were used to substitute 25 to 75 % by weight of both natural coarse and fine aggregates. For blocks with a replacement level of 75 %, a compressive strength of 6.75 MPa and a transverse strength of 1.23 MPa were reported.

Poon *et al*. [2002] successfully designed a patented technology in using a mechanized moulding method for producing concrete bricks and paving blocks. The method can replace both the fine and coarse natural aggregates by local recycled aggregates in making the precast products. Using this technique, concrete paving blocks complying with the requirements of the General Specifications [CEDD, 1992] with a compressive strength of not less than 30 MPa can be produced. The recent developments have shown obvious advantages and proven that recycling C&DW and reusing recycled aggregate in masonry units is feasible. Products including partitioning walls, road dividers, bridge fencing, noise barriers and paving blocks can be produced, all of which do not require high quality standards.

On the other hand, Soutsos *et al* [2004] suggested that the C&DW can be used in concrete building blocks. They found that high recycled aggregate replacement level had an adverse effect on the blocks, but it was expected that the target strength can be achieved by using a lower replacement level, whilst maintaining economical cement content.

2.5 Recycling of C&DW in Hong Kong

Recycling as a means of sustainable use of materials started in Asia until fairly recently. The progress of recycling of C&D materials is relatively slower in Hong Kong. The major constraint is the lack of knowledge about recycled aggregate (especially in concrete) within the construction industry in Hong Kong. The current problems in landfill and public fill shortage have led to the development of environmentally friendly alternatives. In fact, to recycle C&DW as recycled aggregates for construction could benefit the local economy, as presently 40 % of the aggregate demand in Hong Kong has to be imported from southern China due to the local deficiency [Chan and Fong, 2001]. The remaining 60 % is sourced locally, but if recycled aggregates can be produced from local C&DW, they can act as a substitute for virgin aggregates to meet the necessary demand.

Poon *et al.* [2004b] demonstrated the practical use of paving blocks made using recycled aggregates. The paving blocks were manufactured, paved and monitored locally. Figure 2.5.1 shows one of these sites in Yuen Long which had been laid for almost two years. The study demonstrated that both fine and coarse recycled aggregates could be used to replace virgin aggregates in concrete paving blocks of grade 30.

Figure 2.5.1 Recycled paving blocks in Yuen Long [Poon, 2004b]

In order to initiate the establishment of the recycling market in the Hong Kong government set up the first temporary recycling facility in 2002 at a public filling area in Tuen Mun Area 38, to process inert C&DW into aggregates for use in public projects, research and development works in Hong Kong. The plant was designed to cope with a handle capacity of 2400 tonnes of C&DW and a designed output capacity of 1200 tonnes of recycled aggregates per day [CEDD, 2004]. The plant produced recycled coarse aggregates (40, 20 and 10 mm), recycled fine aggregates (<5 mm) and recycled rock fill (grade 20). Over two and a half years the plant produced 441,963 tonnes of recycled aggregate for beneficial reuse in construction works. However, the plant was closed in 2005.

2.6 Recent policy

Another recent step forward is that a charging scheme for C&DW disposal has been implemented [EPD, 2005]. The scheme details that inert waste going to public fills should be charged at HK$27/ton. Mixed waste going to sorting facilities with at least half comprising inert waste should be charged at HK$100/ton. And mixed waste going to landfills with less than half comprising of inert waste should be charged at HK$125/ton. The aim of the charging scheme is that construction waste producers are encouraged to reduce, sort and recycle construction waste so that their disposal costs can be minimized and the valuable landfill space can be preserved. The Charging Scheme has come into operation on **1 December 2005**. The charging fee and construction waste classification are shown in the following Table:

Table 2.6.1 The charging fee of the construction and demolition waste

Government waste disposal facilities	Type of construction waste accepted	Charge per tonne#
Public fill reception facilities	Consisting entirely of inert construction waste++	$27
Sorting facilities	Containing more than 50% by weight of inert construction waste++	$100
Landfills@	Containing not more than 50% by weight of inert construction waste++	$125
Outlying Islands Transfer Facilities@	Containing any percentage of inert construction waste++	$125

In October 2004, the Environment, Transport and Works Bureau [ETWB, 2004] published a document to promote the use of concrete paving blocks prepared with recycled aggregate. The purposes of this document was to encourage local contractors to utilize the blocks and to also to provide a recognized specification for the blocks. This document suggested that aggregates for paving block production showed contain not less than 70% by weight of recycled aggregates and the recycled fine aggregates shall constitute not less than 40% by weight of the total recycled aggregates. The document (Table 2.6.2) also mentioned the classification of the concrete paving blocks prepared with recycled aggregates. Two grades of block were classified (Grades A and B) depending on their quality. Grade B block should have a characteristic strength of not less than 30MPa and 45MPa for footways and vehicles respectively. There are four more criteria for Grade A block: Dimension deviation, skid resistance, abrasive resistance and water absorption.

Table 2.6.2 Standards of different grades of paving blocks

Requirement		Grade A	Grade B
Compressive strength (MPa)	for pedestrian	≧30	≧ 30
	for vehicles	≧45	≧ 45
Skid resistance (BPN)		≧45	-
Abrasive resistance (mm)		≦23	-
Cold water absorption (%)		≦6	-

2.7 Parameters affect the performance of the concrete blocks

Actually, the properties of the paving blocks can be improved by varying the mix proportion because the quality of the paving blocks is governed generally by the two factors according to Shackel [1990]: aggregate to cement (A/C) ratio and aggregate grading

2.7.1 Aggregates to cement (A/C) ratio

The A/C ratio can be expressed in terms of the cement content. Increasing A/C ratio is the same as decreasing cement content. In concrete, decreasing the cement content (increasing the proportion of aggregate) in the mix will at a constant w/c ratio, produce a small increase in concrete strength [Erntroy and Shacklock, 1954]. This has been attributed to an increase in the aggregate concentration, which produced a great number of secondary cracks prior to failure. This effect is valid if the paste content remains high enough to at least fill the voids in the coarse/fine aggregate system, thereby allowing complete consolidation of the concrete. This therefore imposes a maximum limit to aggregate content for practical concretes. However, in concrete blocks, the size of coarse aggregate in the mix is usually less than 10mm and secondary cracks on the small aggregates were probably insignificant. As the w/c ratio is usually less than 0.4 in the mix of concrete paving block, the strength of hardened cement paste is higher than

75MPa [Domone and Thurairatnam, 1986].

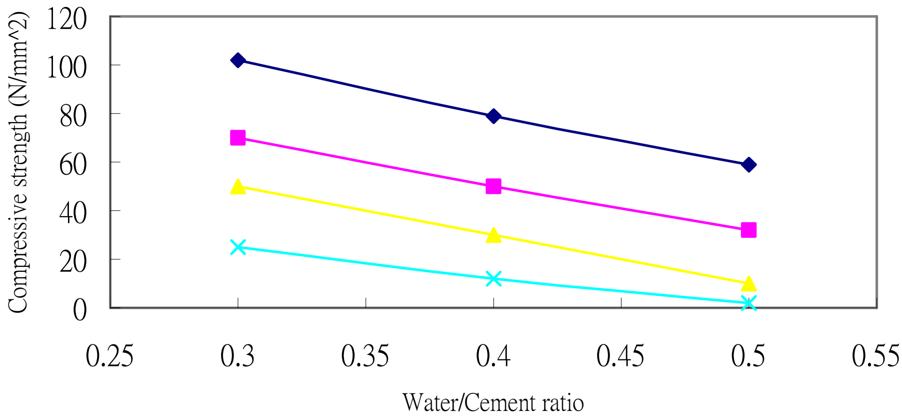


Figure 2.7.1 Relationship between compressive strength and water/cement ratio [Domone et al., 1986]

Therefore, A/C ratio may be a dominant factor on the performance of concrete block. According to the results from Ghafoor and Smith.[1993], the compressive strength, density, water absorption and tensile splitting were improved as decrease with A/C ratio.

2.7.2 Grading

The grading of a granular mix has a close relevance to the properties of concrete. The optimal material grading has the lowest possible surface and void content per unit volume, thus requiring the lowest possible water and cement content to achieve the desired workability, strength and other concrete properties. The grading, also, affects the cost of concrete products, because if the aggregate particles are packed well, less cement is required to achieve the desirable strength and hence the cost is decreased.

Much of the literature concerning beneficial effects on concrete strength and density by utilizing graded particles were conducted around 1907 by Fuller and Thompson [1907].

Lee [1970] studied the factors affecting the packing and porosity of particles on aggregates grading for dense asphaltic compositions. In recent decades, Kronlof [1994] and Addis [1992] illustrated the influence of aggregate grading on properties of concrete. Kronlof worked with very fine quartz powder fillers to improve particle packing in silica fume super-plasticized concrete mixtures. He concluded that the strength of concrete can be increased by refining the packing. The improvement can be attributed to a decrease in the water/binder ratio and an increase the strength of the interfacial transition zone (ITZ). On the other hand, Addis noted that the packing density of aggregates did play an important role in affecting the strength of concrete. In the experiment, the aggregates in the two concrete mixtures had the same Fineness Modulus (FM) but with different consolidation bulk densities (CBD). He concluded that higher compressive strength of concrete was achieved when the aggregates with a higher CBD value was used in the concrete mixtures.

The concept of aggregate packing was first noticed since Fuller and Thompson [1907] proposed the ideal grading curve. Less voids between aggregate particles was obtained as the grading curve of the aggregate particles was close to ideal grading curve.

However, in many cases, the quality of the concrete produced was not the best when applying the concept of ideal grading only. The reason is that the workability criterion is not sufficient with the condition of ideal grading curve. According to Power's study [1968], satisfactory quality of concrete required adequate workability. Therefore, for ordinary wet mixed concrete, the application of ideal grading on concrete is limited by the workability requirement. However, the limitation can be overcome when the idea of ideal grading is applied to dry-mixed concrete masonry blocks. As mentioned before, the workability of mix is not a vital factor governing the quality of dry-mixed concrete block produced by mechanized vibration and compaction.

2.7.2.1 Fineness modulus

The fineness modulus (FM) is one of the most widely known and used grading index. It is based on summation of the percentages of aggregates retained on a specified series of sieves. This index is used in the ACI mix design method to adjust for sand fineness [Day, 1995].

2.7.2.2 Ideal grading curve

In order to minimize the amount of cement paste use in concrete, the amount of voids between the aggregates should be the minimum. Fuller and Thompson [1907] developed an ideal grading curve (Fuller curve). Minimum voids between aggregates are obtained, if any of the grading curve match the Fuller curve which can be expressed as:

$$p = \left(\frac{d}{d_{Max}}\right)^q \text{--(Eq.2.1)}$$

Where p = Passing percentage
d = Aggregate size
d_{max} =Maximum aggregate size
q =Empirical parameter (q=0.5)

However, a recent report [Barry, 2003] showed that the constant q varies with the angularity of aggregates. q are 0.5 and 0.38 appropriated for non-angular and some angular aggregate respectively.

Moreover, the weakness of the ideal grading approach is ideal packing rarely possible in real situations.

2.7.2.3 Packing density

With the evolvement of the advanced computer technology in recent decades, various numerical models such Aim's model, Toufar's model (Goltermann *et al.,* 1997) and Compressive Packing Model (CPM) (Larrard, 1999&2002) have been created to calculate the packing density of aggregates. Furthermore, Fu [2003] used a computer program to simulate the aggregate packing randomly. He assumed the aggregates to be spherical in shape and considered the kinematics and dynamitic conditions. This concept was applied to concrete mixes and the result of the computational simulation gave a good agreement with the physical test of the concrete.

Besides, a number of softwares (EUROPE and LCPC-RENE) have been developed based on the Aim's model, Tourfar's model (Goltermann *et al.*, 1997) and compressive packing model (Larrard, 1999&2002) and they can be used to predict the packing density of any granular mixes. Simple explanations of Aim's model, Toufar's model and compressive packing model are shown below:

Aim's model

Aim's model is based on two cases. The first case is when the amount of fine particles are much less than the amount of course particles and the fine particles are used to fill up some of the voids between the coarse aggregates. The second case is when the amount of coarse particles is much less than the amount of fine particles and the coarse particles are embedded in the fine particles. The maximum packing degree of the mix is found:

$y^*=p/(1+p)$---(Eq. 2.2)

$p=\Phi_1/\Phi_2-(1+0.9*d_1/d_2)*\Phi_1$--(Eq. 2.3)

where,

y1,y2= the grain volume of the fine and coarse aggregates respectively

Φ1, Φ2= the eigen-packing degree of the fine and coarse aggregates respectively

d1, d2= the characteristic diameter of fine and coarse aggregate respectively

and the factor (1+0.9*d1/d2) is due to the wall effect. The packing degree can, in the two cases, be calculated by

$\Phi_{=}\Phi_2/(1-y1)$ for $y_1<y^*$---------------------- (Eq. 2.4)

$\Phi=1/[y_1/\Phi_1+(1-y_1)*(1+0.9*d_1/d_2)]$ for $y_1 \geqq y^*$------------------------(Eq. 2.5)

Toufar’s model

Toufar’s model predicts the packing degree by:

$\Phi=1/[y_1/\Phi_1+ y_2/\Phi_2- y_2(1/ \Phi_2-1)*k_d*k_s]$ -------------------------------------(Eq. 2.6)

Where,

y_1/Φ_1 = the bulk volume of the fine particles

y_2/Φ_2 = the bulk volume of the coarse particles

$y_2(1/ \Phi_2-1)$ =the void volume between the coarse particle

k_d = a factor that determines the influence of the diameter ratio

k_s =a statistical factor

Toufar, Klose, and Born state that

$k_d = (d_2 - d_1)(d_1 + d_2)$ --(Eq. 2.7)

and that each of the fine particles are placed between four coarse particles

Compressive packing model (CPM)

The CPM is based on the concept of virtual packing density and compaction index. The virtual packing density is defined as the maximum packing density achievable within a given mixture, each particle keeping its original shape and being placed one by one. The virtual packing density was also affected by the loosening and wall effects as shown in Figures 2.7.2.1 and 2.7.2.2 respectively.

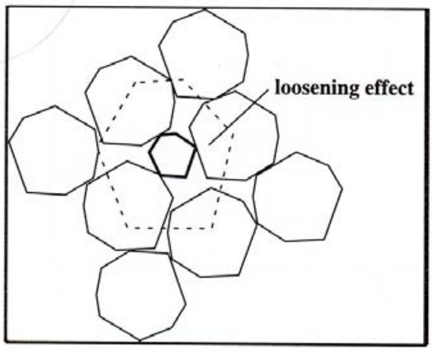


Fig. 2.7.2.1 Loosening effect

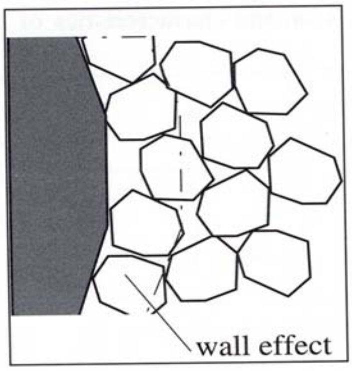


Fig. 2.7.2.2 Wall effect (Larrard, 1999)

A compaction index, K, is a factor which the actual packing density is close to virtual one. Therefore, K is a characteristic of the placing process. Appropriated compaction index can give accurate prediction of the theoretical packing density.

2.7.3 Aggregate properties

Other than grading and A/C ratio, the aggregate property is probably the major factor affecting paving block properties. Poon *et al.* [2005a] showed that when the paving block was prepared with recycled concrete aggregate and crushed clay brick, the water absorption of the paving was increased sharply and was directly proportional to clay brick content. They also found that the aggregate crushing strength had a close relationship with the strength of prepared paving blocks.

Moreover, Poon et al. [2005b] also demonstrated the practical use of paving blocks made using recycled crushed glass. It is possible to mix the C&DW with the recycled crushed glass to compensate the high water absorption of paving block resulting from C&DW.

In Hong Kong, about 300 tonnes of waste glass is generated everyday. However, the recycling rate is low where 98 % of the waste glass is disposed of at landfills. In other countries, the waste glass is crushed into specified sizes as aggregates for water filtration, grit blasting, sand cover for sport turf and sand replacement in concrete [WRAP, 2005].

In Australia, RCG is used as a sand replacement in concrete pavement [Sagoe-Crentsil *et al.*, 2001]. However, the concrete strength is found to be reduced by 5% and 27 % when the glass replacement levels are at 5% to 30 % respectively. Nevertheless, low drying shrinkage is observed for concrete prepared with recycled crushed glass (RCG) as a partial replacement of sand. According to New York State Energy Research and Development Authority [NYSERDA, 1997], RCG is employed as aggregates in the production of concrete masonry in the United States. Test results show that the use of RCG reduces the strength and water absorption of the concrete blocks. Furthermore, both CSIRO and NYSERDA found that alkali-silica reaction (ASR) would occur when crushed glass is used in cement-based materials like concrete. ASR [West, 1996] occurs in concrete when alkalis from the cement reacts with free silica presented in certain aggregates to form alkali-silica gels. The alkali-silica gels have the property of taking in water and expanding, which causes permanent damage to the concrete. Nevertheless, the reaction only occurs if and only if all three conditions take places at the same time: 1) the presence of alkalis in the cement paste, 2) the presence of a reactive aggregate in the concrete and 3) a supply of water. The reaction would not occur if any of the above conditions is not present.

ASR can be prevented by adding mineral admixtures in the concrete mixture. Common mineral admixtures used to minimize ASR are Pulverized Fuel Ash (PFA), silica fume

(SF) and Metakaolin (MK) and a number of studies [NYSERDA,1997, Swamy,1992, Zhu and Byars, 2004] have already proven the suppressing ability of these materials on ASR. In addition, Turanli *et al.*[2003] also found that it was possible to use ground clay brick as a pozzolanic material to minimize the ASR reaction.

Chapter 3 Materials, mix proportions and tested methods

3.1 Materials

3.1.1 Ordinary Portland cement (OPC)

The cementitous material used in this study was an Ordinary Portland Cement (OPC), complying with BS 12 [BS, 1996] and ASTM Type I [ASTM, 2004]. This type of OPC is commercially available in Hong Kong and is often used as the setting agent for general concrete works such as for floors, reinforced concrete structures, pavements etc. The properties of the OPC are shown in Table 3.1.

3.1.2 Pulverised fly ash (PFA)

PFA is a by-product of coal-fired electricity generation, but it is the finer material that is transported by the flue gases to the particle removal system, where it is collected. PFA is commercially available. Low calcium pulverized fly ash (PFA) equivalent to ASTM C618 Class F [ASTM, 2003a] from a local source was used in this study. The properties of the PFA are shown in Table 3.1.

3.1.3 Metakaolin (MK)

Metakaolin (MK) is a thermally activated alumino-silicate produced from kaolinite clay through a calcining process. Similar to silica fume it reacts aggressively with calcium hydroxide and hence is used as a supplementary cementitious material with pozzolanic properties. The addition of MK in concrete is visually appealing as the colour is lightened due to MK's white nature. In this study, MK was imported from Indonesia. The properties of the MK are shown in Table 3.1.

Table 3.1 Properties of cementitious materials

	Cement	PFA	Metakaolin (MK)
SiO_2 (%)	19.61	56.79	53.20
Fe_2O_3 (%)	3.32	5.31	0.38
Al_2O_3 (%)	7.33	28.21	43.90
CaO (%)	63.15	<3	0.02
MgO (%)	2.54	5.21	0.05
SO_3 (%)	2.13	0.68	-
Na_2O (%)	-	-	0.17
K_2O (%)	-	-	0.10
TiO_2 (%)	-	-	1.68
Loss on ignition (%)	2.97	3.90	0.50
Density (kg/m^3)	3160	2310	2620
Specific surface area (cm^2/g)	3520	3960	12680

3.1.4 Natural aggregates (NA)

Crushed granite was used as the natural aggregates. Two nominal sizes, 10mm and < 5 mm, were used and were referred to as natural coarse aggregate (NCA) and natural crushed fine aggregate (NFA) respectively. The sieve analysis of the NCA and NFA are shown in Figure 3.1b and 3.1a respectively. Their physical properties of the recycled aggregates are shown in Table 3.2.

3.1.5 Recycled aggregates (RA)

The RA used in this study was crushed and sorted inert C&D wastes(the impurities: Glass, bricks, titles and etc <1% and density less than water materials < 0.5%, mainly were stone and broken concrete) sourced from Tuen Mun Area 38, which is a temporary recycling facility for C&D waste in Hong Kong. In the plant the inert C&D waste underwent a process of mechanized crushing and sieving to produce both fine and coarse aggregates according to the particle size requirements of BS 812 [BS, 1985] and to remove excess impurities which would affect the performance of the aggregates. In this study, 10 mm and < 5mm RA, referred to as recycled coarse aggregate (RCA) and recycled fine aggregate (RFA) respectively, were used. The sieve analysis of the RCA and RFA are shown in Figure 3.1b and 3.1a respectively. Their physical properties of the recycled aggregates are shown in Table 3.2.

3.1.6 Recycled crushed glass (RCG)

The recycled crushed glass (RCG) used in this study was mainly post-consumer beverage bottles sourced locally. The glass bottles were washed and crushed mechanically. The RCG was sieved in the laboratory to produce the < 5 mm aggregates. The RCG was a blend of 3 different types of beverage glasses with three different colors (30% Colorless, 40% Green and 30% Brown). The grading of the RCG satisfied the requirement for fine aggregates according to BS 882 [BS, 1992] after sieving. The sieve analysis and physical properties of the recycled crushed glass are shown in Figure 3.2a and Table 3.2 respectively.

3.1.7 Sand

The sand used was fine natural river sand commercially available in Hong Kong. The sieve analysis and physical properties of the sand are shown in Figure 3.1a and Table 3.2 respectively. The fineness modulus value of the sand is 2.3.

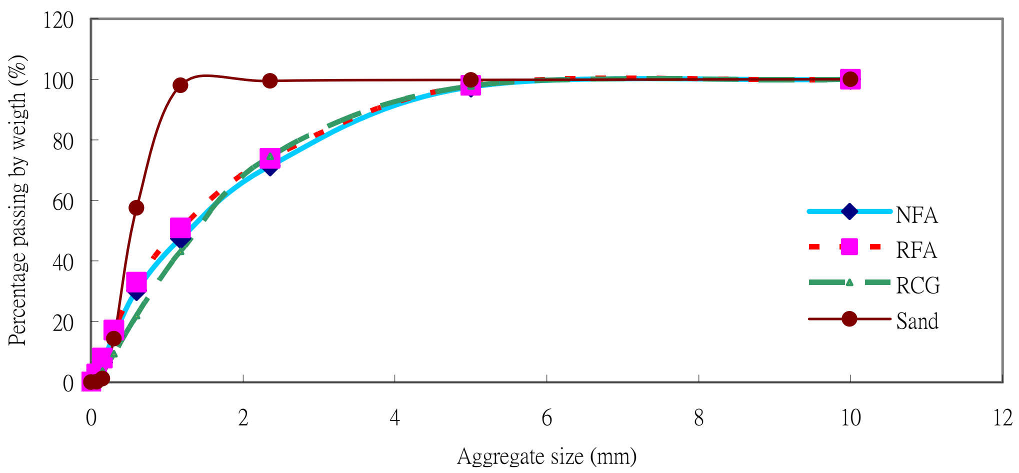


Figure 3.1a Grading curves of NFA, RFA, RCG and sand.

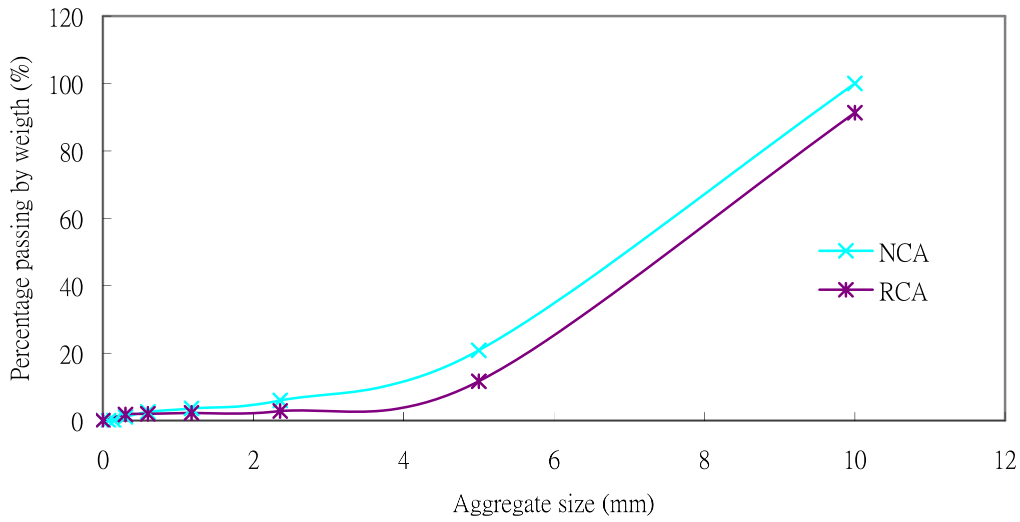


Figure 3.2b Grading curves of NFA, RFA, RCG and sand.

Table 3.2 Properties of NFA, RFA, RCG, NCA, RCA and Sand

	Density (kg/m^3)	Water Absorption (%)	10% Fine Value (kN)
RCG	2500	~0	107
NFA	2630	3	150
RFA	2530	10.3	120
Sand	2620	1	-
NCA	2650	1.2	157
RCA	2550	3	120

3.2 Mix proportions:

3.2.1a Dry-mixed method

In most of concrete block production, a dry mixing method is used in order to increase productivity. In the real manufacturing situation, a low W/C ratio is recommended for preparing the dry mixed concrete blocks in order to form and keep the required shape of the blocks after the blocks are removed from the mould. The compaction and vibration of the materials in the moulds only last for several seconds and ater which the moulds would be removed and the blocks are required to maintain their shape by adhesive forces between the particles. The advantages of the dry mixing method is that the blocks can be formed after several seconds of compaction and vibration within the mould and only one set of mould is necessary to produce thousands of the blocks. In reality, there is no exact W/C ratio used for preparing the the dry mixes. Therefore, although W/C ratio is the main parameter for controlling the strength of wet-mixed normal concrete, it is not the case for the dry-mixed blocks. In this study, the effect of W/C ratio is not the main controlling parameter on strength and other properties. Rather, A/C ratio, grading and aggregate properties are considered as the main parameters that affect the dry-mixed block properties.

In the experimental study, the concrete block samples were prepared by using manual hammering followed by compacting by a loading machine in order to stimulate the real situation. Normally, the initial amount of water added (about one tenth of the total weight of aggregates) was more than that was required to ensure sufficient hydration of the cement but it was observed that some excess water was forced out from the moulds during the compacting process.

Figure 3.2.1a Water leak from the mould

3.2.1 Mix proportions: The effect of aggregates to cement (A/C) ratio and types of aggregate on the properties of pre-cast concrete blocks (Chapter 4)

The first phase of the experimental work is divided into two parts. The first part was to determine the effects of A/C ratios on the properties of blocks prepared with different types of aggregates. The second part of this section was to evaluate the influences of the combinations of aggregates on the properties of the blocks.

In part one, three series of concrete mixtures (Series I, II and III) were prepared initially. Series I, II and III were prepared with NFA, RFA and RCG as shown in 3.2.1.1, Table 3.2.1.2 and Table 3.2.1.3, respectively. In each series, aggregate-to-cement (A/C) ratios of 3, 4 and 6 were used to investigate the effects of different A/C ratios on the properties of the blocks. In addition, concrete mixtures with A/C ratios of 10 and 13 were also prepared in Series III in order to further investigate the effect of low cement content on properties of the blocks prepared with RFA. The results were useful for block works that are intended for non-loadbearing application (e.g. partition blocks).

In part two, three mores series of concrete mixtures were prepared. Three concrete mixtures were prepared in Series IV (Table 3.2.1.4) in which the blocks were prepared with 50 % RCG and 50 % RFA but with varying A/C ratios from 3 to 6. There results were then compared with those of Series II and III to determine the effects of blending two types of aggregates on the properties of the blocks. In Series V (Table 3.2.1.5), RFA was used to replace 0 %, 25 %, 50 %, 75 % and 100 % NFA in the production of the concrete blocks which had an A/C ratio of 4. Similarly, in Series VI (Table 3.2.1.6), RCG was used to replace 0 %, 25 %, 50 %, 75 % and 100 % RFA in the concrete mixtures prepared with an A/C ratio of 4. The influences as a result of the incorporation of RFA and RCG on the properties of blocks will be addressed.

Table 3.2.1.1 Mix proportions of concrete mixtures in Series I

Notations	RCG (kg)	NCA (kg)	RCA (kg)	Cement (kg)	A/C ratio	Added water (kg)
NFA-3	-	23	-	7.7	3	2.1
NFA-4	-	23	-	5.8	4	2.0
NFA-6	-	23	-	3.8	6	2.0

Table 3.2.1.2 Mix proportions of concrete mixtures in Series II

Notations	RCG (kg)	NCA (kg)	RCA (kg)	Cement (kg)	A/C ratio	Added water (kg)
RCG-3	23	-	-	7.7	3	2.0
RCG-4	23	-	-	5.8	4	2.1
RCG-6	23	-	-	3.8	6	2.0

Table 3.2.1.3 Mix proportions of concrete mixtures in Series III

Notations	RCG (kg)	NCA (kg)	RCA (kg)	Cement (kg)	A/C ratio	Added water (kg)
RFA-3	-	-	23	7.7	3	2.5
RFA-4	-	-	23	5.8	4	2.3
RFA-6	-	-	23	3.8	6	2.3
RFA-10	-	-	23	2.3	10	2.1
RFA-13	-	-	23	1.8	13	2.0

Table 3.2.1.4 Mix proportions of concrete mixtures in Series IV

Notations	RCG (kg)	NCA (kg)	RCA (kg)	Cement (kg)	A/C ratio	Added water (kg)
50RFA/RCG-3	11.5	11.5	-	7.7	3	2.2
50RFA/RCG-4	11.5	11.5	-	5.8	4	1.9
50RFA/RCG-6	11.5	11.5	-	3.8	6	1.9

Table 3.2.1.5 Mix proportions of concrete mixtures in Series V

Notations	RCG (kg)	NCA (kg)	RCA (kg)	Cement (kg)	A/C ratio	Added water (kg)
NFA-4	23	-	-	5.8	4	2.3
25RFA/NFA-4	-	17.2	5.8	5.8	4	2.2
50RFA/NFA-4	-	11.5	11.5	5.8	4	2.1
75RFA/NFA-4	-	5.8	17.2	5.8	4	2.1
RFA-4	-	-	23	5.8	4	2.0

Table 3.2.1.6 Mix proportions of concrete mixtures in Series VI

Notations	RCG (kg)	NCA (kg)	RCA (kg)	Cement (kg)	A/C ratio	Added water (kg)
RCG-4	23	-	-	5.8	4	2.3
25RFA/RCG-4	-	17.2	5.8	5.8	4	2.1
50RFA/RCG-4	-	11.5	11.5	5.8	4	2.1
75RFA/RCG-4	-	5.8	17.2	5.8	4	2.0
RFA-4	-	-	23	5.8	4	2.1

3.2.2 Mix proportions: The effect of aggregate grading on the engineering properties of concrete blocks (Chapter 5)

In Series VII, concrete blocks with an aggregate-to-cement (A/C) ratio of 4 were prepared with 16 different graded recycled aggregates (RFA + RCA) in order to determine the ideal grading curve. The sieve analysis of the graded aggregates is shown in Table 3.4.7.1. After determining the ideal grading curves for the block production, the respective optimal fineness modulus (FM) of the blended aggregates was calculated.

In the second stage of the study three more series of mixes were prepared with an A/C ratio of 4. The concrete mixtures in Series VIII, IX and X were prepared with different types of coarse and fine aggregates with varying FM to study if the origin of the aggregate was a factor affecting the optimal FM for the production of the concrete blocks. The concrete blocks in Series VIII was prepared with natural aggregates (NFA and NCA). The concrete mixtures in Series IX were prepared with river sand and NCA, and the mixtures in Series X were prepared with river sand and RCA. The mix proportions of concrete mixtures in Series VIII, IX and X are shown in Tables 3.2.2.1, 3.2.2.2 and 3.2.2.3 respectively.

Table 3.2.2.1 – Mix proportions of concrete mixtures in Series VIII

Notations	NCA (kg)	NFA (kg)	Cement (kg)	Added water (kg)
100NFA	-	23	5.75	2.0
20NCA80NFA	4.6	18.4	5.75	1.9
35NCA65NFA	8.05	14.95	5.75	2.0
50NCA50NFA	11.5	11.5	5.75	2.0
80NCA20NFA	18.4	4.6	5.75	1.7
100NCA	23	-	5.75	1.6

Table 3.2.2.2 – Mix proportions of concrete mixtures in Series IX

Notations	NCA (kg)	Sand (kg)	Cement (kg)	Added water (kg)
20NCA80S	4.6	18.4	5.75	1.8
35NCA65S	8.05	14.95	5.75	1.7
50NCA50S	11.5	11.5	5.75	1.8
80NCA20S	18.4	4.6	5.75	1.7

Table 3.2.2.3 – Mix proportions of concrete mixtures in Series X

Notations	RCA (kg)	Sand (kg)	Cement (kg)	Added water (kg)
100S	-	23	5.75	1.6
20RCA80S	4.6	18.4	5.75	1.8
35RCA65S	8.05	14.95	5.75	1.9
50RCA50S	11.5	11.5	5.75	1.6
80RCA20S	18.4	4.6	5.75	1.6
100RCA	23	-	5.75	1.5

3.2.3 Mix proportions: Durability of concrete blocks prepared with recycled crushed glass- ASR consideration (Chapter 6)

The potential ASR expansion of the prepared mortar bars was assessed in accordance with ASTM C1260. Seven series of mortar bars were prepared in total. In Series I-M, three mortar bar mixes were prepared with RCG and sand in different proportions (Table 3.2.3.1) in order to determine the ASR expansion of mortar bars without any suppressant. Since the incorporation of mineral admixtures is known to be able to mitigate the potential expansive reaction as a result of ASR, mortar bars with 50% RCG and 50% sand were prepared with the incorporation of PFA and MK in Series II-M and III-M, respectively, (Table 3.2.3.1) to evaluate the effectiveness of using PFA and MK as a suppressant of ASR. The dosages of PFA and MK were 2.5, 5 and 10 % by weight of the total aggregates. Based on the results of Series I-M, II-M and III-M, the use of either PFA or MK as the ASR suppressant for the subsequent tests was determined.

Table 3.2.3.1 - Mix proportions of mortar bars in Series I-M to III-M

Notations	Cement (g)	RCG (g)	Sand (g)	PFA (g)	MK (g)
Series I-M					
100G	440	990	-	-	-
50G50S	440	495	495	-	-
100S	440	-	990	-	-
Series II-M					
50G50S2.5M	440	495	495	-	24.8
50G50S5M	440	495	495	-	49.5
50G50S10M	440	495	495	-	99.0
Series III-M					
50G50S2.5P	440	495	495	24.8	-
50G50S5P	440	495	495	49.5	-
50G50S10P	440	495	495	99.0	-

Note: G=RCG, S= Sand, M= MK, P=PFA

In the subsequent tests, a similar approach as in Series I-M, II-M, and III-M was used to evaluate the ASR reactivity of RCG when it is blended with RFA. Four mortar bar mixes were prepared with RFA and RCG in different proportions without any mineral admixtures in Series IV-M (Table3.2.3.2) to determine the maximum allowable RCG content without the use of suppressant. In Series V-M, PFA (found to be the better suppressant) was added at 5 %, 10 % and 15 % by weight of total aggregates to the mortar bars samples which were prepared with 75 % RCG and 25 % RFA. Similarly, PFA was added at the same dosages to the mortar bar samples which were prepared with 50 % RCG and 50 % RFA and 25 % RCG and 75 % RFA in Series VI-M and VII-M respectively (Table3.2.3.2). According to the results of Series V-M to VII-M, the adequate amount of PFA needed to suppress the ASR for different RCG contents were summarized.

Table 3.2.3.2 - Mix proportions of mortar bars in Series IV-M to VII-M

Notations	Cement (g)	RCG (g)	RFA (g)	PFA (g)
Series IV-M				
75G25R	440	742.5	247.5	-
50G50R	440	495	495	-
25G75R	440	247.5	742.5	-
100R	440	-	990	-
Series V-M				
75G25R5P	440	742.5	247.5	49.5
75G25R10P	440	742.5	247.5	99.0
75G25R15P	440	742.5	247.5	148.5
Series VI-M				
50G50R5P	440	495	495	49.5
50G50R10P	440	495	495	99.0
50G50R15P	440	495	495	148.5
Series VII-M				
25G75R5P	440	247.5	742.5	49.5
25G75R10P	440	247.5	742.5	99.0
25G75R15P	440	247.5	742.5	148.5

Note: G=RCG, R= Recycled aggregate, P=PFA

3.2.4 Mix proportions:_The properties of concrete blocks prepared with recycled aggregate and recycled crushed glass with addition of PFA (Chapter 7)

A total of three series of mixtures were prepared for producing the concrete blocks prepared with RCG and RFA. The RCG to RFA ratios were 3 to 1, 1 to 1 and 1 to 3 in Series XI, XII and XIII respectively. The PFA was added at dosages of 5, 10 and 15 % by the weight of total aggregates in each series. The mix proportions are shown in Table 3.2.4.1 where an aggregate-to-cement ratio of 4 was used.

Table 3.2.4.1 - Mix proportions of concrete blocks

Notations	Cement (kg)	PFA (kg)	RCG (kg)	RFA (kg)
Series XI				
75G25R	5.75	-	5.75	17.25
75G25R5P	5.75	1.15	5.75	17.25
75G25R10P	5.75	2.30	5.75	17.25
75G25R15P	5.75	3.45	5.75	17.25
Series XII				
50G50R	5.75	-	11.5	11.5
50G50R5P	5.75	1.15	11.5	11.5
50G50R10P	5.75	2.30	11.5	11.5
50G50R15P	5.75	3.45	11.5	11.5
Series XIII				
25G75R	5.75	-	17.25	5.75
25G75R5P	5.75	1.15	17.25	5.75
25G75R10P	5.75	2.30	17.25	5.75
25G75R15P	5.75	3.45	17.25	5.75

Note: G=RCG, R= Recycled aggregate, P=PFA

3.3 Sample preparation

3.3.1 Block preparation procedure-dry mix method

Aggregates, cement and additives (e.g. PFA) were added into the drum mixer first and were mixed thoroughly. Water was added by measuring about 8% of the total weight of aggregates (Depend on the water absorption of the aggregates and cement content) and mixed them thoroughly. Water was added again until the mixes reached a suitable

Figure 3.3.1.1 Dry mixture with suitable consistence

consistency and moisture content (Figure 3.3.2.1).

3.3.2 Fabrication of blocks

Concrete blocks were fabricated in steel moulds (Figure 3.3.2.2) with internal dimension of 200mm in length, 100mm in width, and 60mm in depth. The dry mixed material (very low w/c ratio) was weighted about 3kg and filled into the mould with

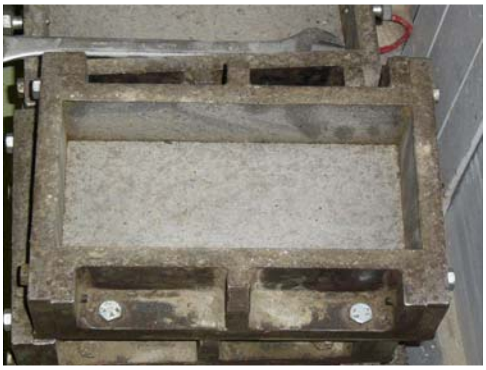


Figure 3.3.2.1 Steel Mould

three layers. Each layer was compacted before filling the mixed materials for next layer. The first two layers were compacted by hammering a wooden prism on the layers (Figure 3.3.2.2). The third layer (Upper) was filled much higher than the mould (about 5-8mm) and was compacted by machine (Figure 3.3. 2.3). The specimens were covered by a plastic sheet to avoid loss of water. After one day, the blocks were removed from their moulds and cured in water for 28 days (Figure 3.3.2.4).

Figure 3.3.2.2 Manual compaction

Figure 3.3.2.3 Mechanical compaction

Figure 3.3.2.4 Water curing

3.3.3 Fabrication of mortar bars for ASR measurement-Wet mix method

The preparation method of the mortar bars followed the method in ASTM C1260 [2001]. The steel moulds were with internal dimensions of 285x25x25 mm (Figure 3.3.3.1). The aggregate grading, cement content, water to cement ratio and compacting method were according to the ASTM standard. The aggregate mixtures were sieved into a specified grading as shown in Table3.3.3.1. The W/C ratio of the mortar bars was equal to 0.47 and the aggregate to cement ratio was 9.9 to 4.4. Additional additives were added into the mixes in order to reduce ASR expansion.

Figure 3.3.3.1 Steel mould

Table 3.3.3.1 Grading requirements

Sieve analysis		Mass %
Passing	Retained on	
4.75mm	2.36mm	10
2.36mm	1.18mm	25
1.18mm	600um	25
600um	300um	25
300um	150um	15

3.4 Test methods

3.4.1 Measurement of mortar bar expansion

The measurement was according to ASTM C1260 [2001]. .Mortar bars were demand 24 hr after casting and placed a 80°C water bath for 24hr. The initial reading of the mortar bars was measured. Then, the mortar bars was soaked in a 1 N sodium hydroxide solution and the expansion was measured at different times (1, 3, 4, 7, 14 and 28 days). A digital dial gauge (Figure 3.4.1.1), with 0.001mm accuracy, was used to measure the expansion of the mortar bars

Figure 3.4.1.1 Dial gauge

3.4.2 Compressive strength

The compressive strength of the specimens was measured according to BS 6717 [1993]. The breaking load was determined using a Denison compression machine with a maximum capacity of 3000 KN. Before loading the specimens were packed with plywood top and bottom (Figure 3.4.2.1). The compressive load was then applied to the strength test face with a nominal area of

Figure 3.4.2.1 Compressive

200x100 mm at a rate of 400 kN per minute until the specimens failed. The compressive strength was determined by dividing the maximum load by the load area of the specimen.

3.4.3 Density

The density of the specimens was determined using the water displacement method, according to the BS standard [BS 1881, 1983].

3.4.4 Water absorption

Water absorption of the specimens was determined according to AS/NZS 4456.14 [2003]. The percentage of cold water absorption was determined by dividing the difference of the weights of specimens after being soaked in cold water (24°C) and after oven dried by the weight of specimens after oven dried. The specimen should be surface dried before measuring the weight after soaked in cold water.

3.4.5 Skid resistance

The surface frictional properties were determined using a British pendulum skid resistance tester (Figure 3.4.5.1) according to BS 6717 [2001]. The skid resistance of the

Figure 3.4.5.1 Skid resistance Tester

specimen surface is expressed as the measured British Pendulum Number (BPN). The specimen surface should be wetted before testing. The result was read directly from the tester after releasing the arm of the pendulum.

3.4.6 Abrasive resistance

The abrasive resistance of specimens was determined by measuring the groove on the block surfaces after abrading with an abrasive material (steel sand) according to BS 6717 [2001]. The apparatus set up used to perform the abrading is shown in Figures 3.4.6.1 and 3.4.6.2. The wheel rotated at about 75 revolutions per minute and the steel sand converged on the surface of the specimen. The steel sand abraded the specimen surface by the wheel for a minute. Then, the width of the groove was measured (Requirement <23mm)

Figure 3.4.6.1 Apparatus for abrasive resistance test

Figure 3.4.6.2 A concrete block hold in the apparatus

3.4.7 Determination of ideal grading curve

In order to produce the ideal grading curve for the concrete blocks, the aggregates were sieved and sorted into six classes (Classes A, B, C, D, E and F) according to their sizes (10-5mm, 5-2.36mm, 2.36-1.18mm, 1.18-0.6mm, 0.6-0.3mm and less than 0.3mm). Initially, the two coarsest size fractions of the aggregate were used to prepare the concrete blocks. After determining the optimal relative proportion and hence aggregate grading which led to the highest compressive strength, the next aggregate size was incorporated into the previously obtained optimal grading to determine the new optimal with an additional aggregate size. These steps were repeated until the smallest aggregate size (i.e. E) was incorporated into the mix proportion. The ideal grading curve was defined as the grading of aggregate which led to the highest strength of the concrete blocks when all six classes of aggregate were used as shown in 3.4.7.1. The size distribution of graded recycled aggregate is shown in Table 3.4.7.1.

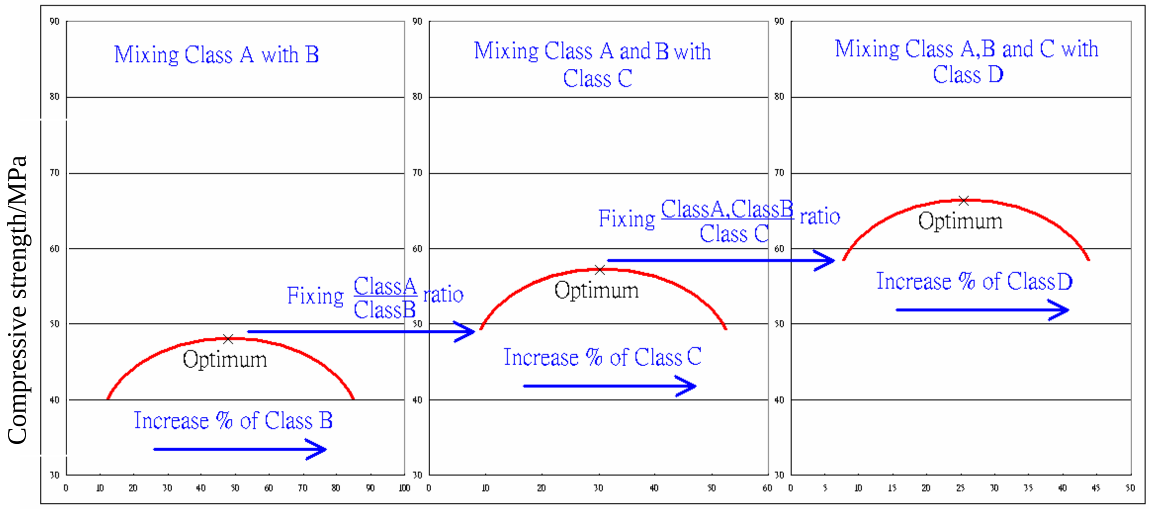


Figure 3.4.7.1 A simple diagram of ideal grading curve approach

Table 3.4.7.1 Size distribution of graded recycled aggregate

	Notations	Passing percentage (%)						
		10mm	5mm.	2.36mm	1.18mm	0.6mm	0.3mm	Remained
	I-5-1	100	0	0	0	0	0	0
	I-5-2	100	40	0	0	0	0	0
	I-5-3	100	60	0	0	0	0	0
	I-5-4	100	80	0	0	0	0	0
Add 2.36mm	I-236-1	100	52	20	0	0	0	0
	I-236-2	100	64	40	0	0	0	0
	I-236-3	100	70	50	0	0	0	0
	I-236-4	100	77.5	62.5	0	0	0	0
Add 1.18mm	I-118-1	100	71.2	52	20	0	0	0
	I-118-2	100	78.4	64	40	0	0	0
	I-118-3	100	88	80	60	0	0	0
Add 0.6mm	I-600-1	100	83	71	52	20	0	0
	I-600-2	100	87	78	64	40	0	0
	I-600-3	100	80.6	67.6	46	10	0	0
Add 0.3mm	I-300-1	100	82.5	70.8	51.4	19	10	0
	I-300-2	100	84.4	74	56.7	27.9	19.9	0

3.4.8 Determination of fineness modulus (FM)

Fineness modulus (FM) represents the fineness of the aggregate – the higher the FM, the coarser the aggregate. It is calculated by summing the cumulative percentages of aggregates retained on each of a specified series of sieves, divided by 100. This index is commonly used in estimating the proportions of coarse and fine aggregates in concrete mixtures. [Day, 1995]

3.4.8 Measurement of actual packing density

This method was modified from the compressive packing density model [Larrard 1999,2000]. The aggregate mixtures were oven dried overnight and allowed to cool to room temperature before the dry density and sieve analysis were determined. 3 kg of the aggregate mixture was prepared and poured into a steel cylinder. The internal diameter and height of the steel cylinder were 150 mm and 260 mm respectively. The cylinder was then placed horizontally and was agitated by a rolling action for about 30 s to ensure the mixture was evenly mixed. The cylinder was then placed on a shaking table before a 10 kg load was added on the top of the sample. Vibration induced by the shaking table was started and settlement after 2 min. vibration was recorded. The procedure was repeated until the difference between the three maximum settlements was less than 0.5mm. The set up of the equipment is shown in Figure 3.4.8.1 to Figure 3.4.8.3. The packing density was calculated according to the following equation:

$$\frac{\sum \frac{W_i}{\gamma_{di}}}{(H-D-T)\pi(\frac{\phi}{2})^2} = \gamma \text{--(Eq3.1)}$$

H: the internal height of the cylinder

D: the settlement measured from the top of the cylinder to the top of the load.

T: the thickness of the load

ϕ: the internal diameter of the cylinder (150mm)

Wi: the mass of each size fractions

Figure 3.4.8.1 Pour aggregates into a steel cylinder

Figure 3.4.8.2 Place the load on the aggregates surface.

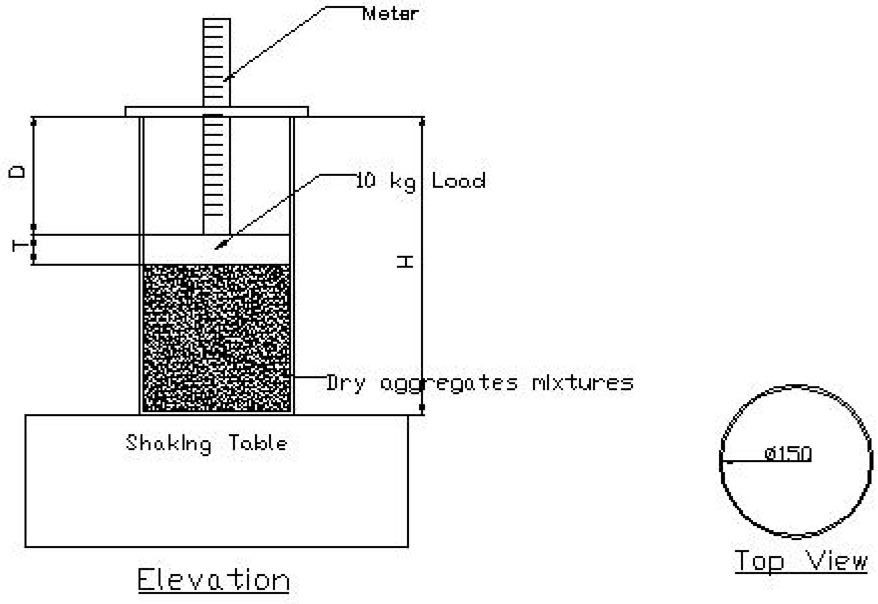


Figure 3.4.8.3 Elevation and top views of the equipment to measure the packing density

3.4.9 Theoretical packing density

According to compressive packing density model [Larrard, 1999], aggregates were sieved into six classes: 10-5mm, 5-2.36mm, 2.36-1.18mm, 1.18-0.6mm, 0.6-0.3mm and less than 0.3mm. The packing density of mono-sized aggregate was then determined for each class according to actual packing density method and Eq. 3.1. The mono-sized aggregate packing density is shown in Table 3.4.9.1. The result showed that the wall effect was not significant except the aggregate sized from 10 to 5mm. Therefore, βi was simplified into $(1+1/K)\Phi'$ and the K was 8. βi is shown on Table 3.4.9.2.

The wall effect and loosening effect were calculated and according to the following equations:

$$a_{ij} = \sqrt{1-(1-d_j/d_i)^{1.02}}$$ --(Eq3.2)

$$b_{ij} = 1-(1-d_i/d_j)^{1.50}$$ --(Eq3..3)

And the virtual packing density was calculated by the following equation.

$$\gamma_i = \frac{\beta_i}{1-\sum_{j=1}^{i-1}\left[1-\beta_i+b_{ij}\beta_i\left(1-1/\beta_j\right)\right]y_j - \sum_{j=i+1}^{n}\left[1-a_{ij}\beta_i/\beta_j\right]y_j}$$ -----------(Eq3..4)

β_i = Virtual packing density of a monodisperse fraction having a diameter equal to di

a $_{ij}$ = Parameter describing the loosening effect exerted by class j on the dominant class i

b $_{ij}$ = Parameter describing the wall effect exerted by class j on the dominant class i

$y_i = \frac{\Phi_i}{\sum_{i=1}^{n}\Phi_i}$, where the partial volume Φ are the volume occupied by each class in unit bulk volume of the granular mix.

The theoretical packing density, Φ, was determined using Eq3.4 and the implicit function (Eq3. 5). In order to solve the above complex calculation, a computer program was written and the display of the program is shown in Figure 3.4.9.1. An algorithm of the computer program is shown in Figure 3.4.9.2.

$$K = \sum_{i=1}^{n} K_i = \sum_{i=1}^{n} \frac{\frac{y_i}{\beta_i}}{\frac{1}{\phi}-\frac{1}{\gamma_i}}$$ --(Eq3.5)

γ_i =Virtual packing density of polydisperse mix, when the I fraction is dominant

Φ =Actual packing density

K =Compaction index

β_i = Virtual packing density of a monodisperse fraction having a diameter equal to di

$y_i = \frac{\Phi_i}{\sum_{i=1}^{n}\Phi_i}$, where the partial volume Φ are the volume occupied by each class in unit bulk volume of the granular mix.

Table 3.4.9.1 Packing density of mono-sized aggregate obtained from experiment

Size range	Weight /kg	Depth /mm	Volume (m^3) Container	Volume (m^3) Aggregate	Packing Density (Φ’)
10-5mm	2.5	93.5	0.001652	0.00094	0.56886
	3	109.5	0.001935	0.001128	0.582845
	3.5	127.8	0.002258	0.001316	0.582617
5-2.36mm	2.5	92.95	0.001643	0.00094	0.572185
	3	110.6	0.001954	0.001128	0.577048
	3.5	129	0.00228	0.001316	0.577197
2.36-1.18mm	2.5	94.75	0.001674	0.00094	0.561315
	3	112.7	0.001992	0.001128	0.566296
	3.5	131.5	0.002324	0.001316	0.566224
1.18-0.6mm	2.5	94.18	0.001664	0.00094	0.564712
	3	113.3	0.002002	0.001128	0.563297
	3.5	132.2	0.002336	0.001316	0.563226
0.6-0.3mm	2.5	94	0.001661	0.00094	0.565794
	3	112.8	0.001993	0.001128	0.565794
	3.5	131.5	0.002324	0.001316	0.566224
<0.3mm	2.5	85.1	0.001504	0.00094	0.624966
	3	102.1	0.001804	0.001128	0.625088
	3.5	119.2	0.002106	0.001316	0.624651

Table 3.4.9.2 βi of mono-sized aggregate

Size range	βi
10-5mm	0.655875
5-2.36mm	0.649125
2.36-1.18mm	0.63675
1.18-0.6mm	0.633375
0.6-0.3mm	0.63675
0.3mm-R	0.703125

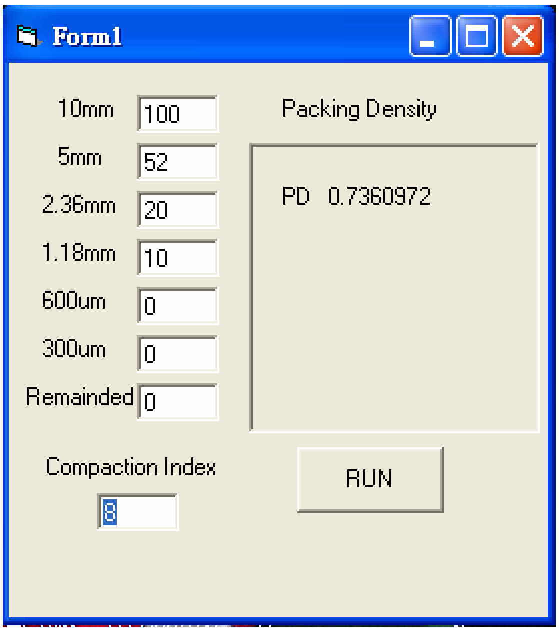


Figure 3.4.9.1.Computer program to calculate the packing density

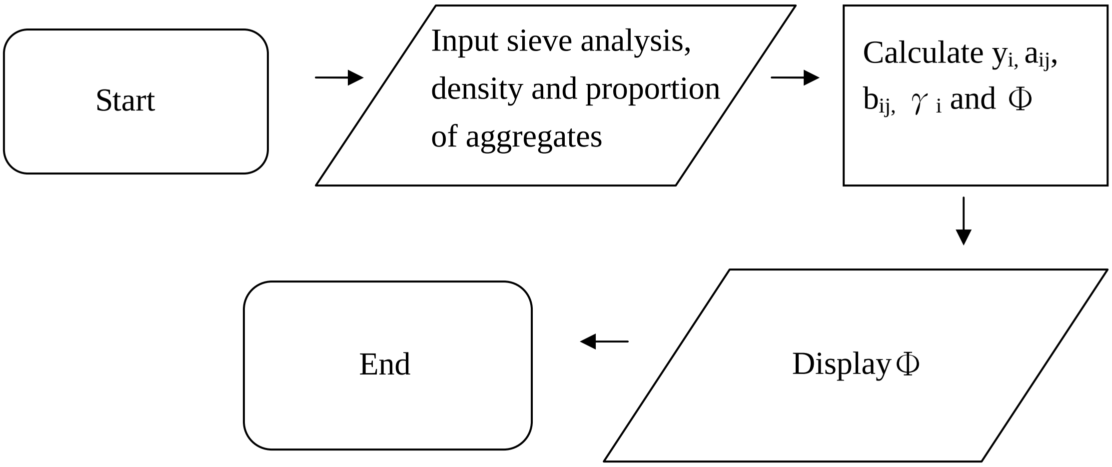


Figure 3.4.9.2 Algorithm of computer program

3.4.10 Verification of the accuracy of the packing density model

In order to verify the computer model developed above, 55 different dry aggregate mixtures were prepared. The mixtures were compacted and their respective actual packing densities were measured while the corresponding theoretical packing density was estimated by the computer program. Figure 3.4.10.1 shows the relationship between the actual packing density and the theoretical packing density. The result reveals that the model gave reasonable predictions of the actual packing density. Therefore it was decided to employ the developed computer model to estimate the actual packing density of concrete mixtures in the subsequent part of the study.

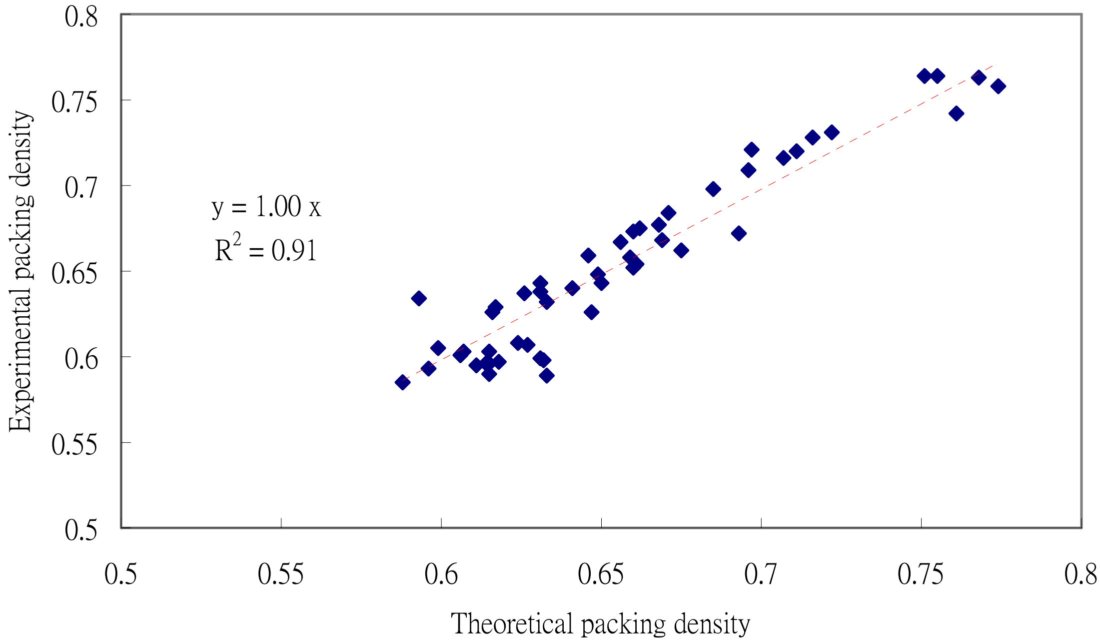


Figure 3.4.10.1 Relationship between the experimental and theoretical packing density

3.4.11 Porosity

According to a previous study [Cheung, 2005], the method required the specimens to be crushed into approximately 10mm diameter sizes and then oven dried at 105 °C for 24 hours. 100 g of the prepared specimens were soaked in acetone in a sealed container for a day. The specimens were then removed from the acetone and the specimen surfaces were dried. The weights of the specimens were then weighed and the difference between the original weights indicated the amount of acetone that can be absorbed by the specimen per 100 g, which is also an approximate indication of the porosity of the specimens.

Chapter 4 The Effect of Aggregates to Cement (A/C) Ratio and Types of Aggregate on the Properties of Pre-cast Concrete Blocks

4.1 Introduction

The effects of aggregate-to-cement (A/C) ratios and types of aggregates on the properties of pre-cast concrete blocks were addressed in this section. A/C ratios between 3 and 6 and three types of aggregates (i.e. natural fine aggregate (NFA), recycled fine aggregate (RFA) and recycled crushed glass (RCG)) were used in the experiments. It was found that the compressive strength of the concrete blocks decreased as the A/C ratio increased. The results showed that the compressive strength was directly proportional to the crushing strength of the aggregates (i.e. 10 % fines value). Moreover, the water absorption of the blocks had a good correlation with the water absorption ability of the aggregate particles. The use of RFA as a replacement of NFA in the production of concrete blocks reduced the density and strength but increased the water absorption of the blocks. However, the potential high water absorption of the blocks as a result of the incorporation of RFA could be ameliorated by the use of RCG since RCG particles had a negligible water absorption value.

4.2 The effects of A/C ratios and types of aggregates on compressive strength

In this section, each presented value is an average of three measurements. The test results of Series I - VI are summarized in Table 4.2.1.

Table 4.2.1 – Test results of blocks in Series I - VI

Mixtures		Density (kg/m^3)	Compressive strength (MPa)	Tensile splitting strength (MPa)	Skid resistance (BPN)	Abrasion resistance (mm)	Water absorption (%)
NFA-3	Series I	2371	85.8	5.0	90	20.5	2.9
NFA-4		2368	79.9	4.2	100	19.5	3.1
NFA-6		2329	50.0	3.1	110	23.0	5.2
RCG-3	Series II	2279	78.0	4.2	90	20.0	4.2
RCG-4		2247	48.6	3.5	105	20.0	3.3
RCG-6		2174	39.1	3.3	105	23.0	2.3
RFA-3	Series III	2288	77.7	5.1	95	20.0	4.1
RFA-4		2242	64.8	3.8	105	20.0	6.3
RFA-6		2175	37.6	2.5	105	22.5	8.4
RFA-10		2166	29.7	2.0	120	25.0	10.0
RFA-13		2120	12.6	0.9	130	26.0	12.0
RFA/RCG-3	Series IV	2250	73.9	4.6	95	19.5	3.2
RFA/RCG-4		2260	58.2	3.4	105	20.5	4.3
RFA/RCG-6		2169	40.0	2.8	105	23.5	5.4
NFA-4	Series V	2368	79.9	4.2	100	19.5	3.1
25RFA/NFA-4		2323	67.4	4.0	105	19	3.5
50RFA/NFA-4		2303	65.8	4.6	102	20	5.1
75RFA/NFA-4		2285	63.5	4.0	98	20	4.8
RFA-4		2242	64.8	3.8	105	20.0	6.3
RCG-4	Series VI	2247	48.6	3.5	105	20.0	3.3
25RFA/RCG-4		2270	57.4	3.1	101	21	3.3
50RFA/RCG-4		2260	53.6	3.4	106	20	4.3
75RFA/RCG-4		2275	60.1	3.9	108	19	4.7
RFA-4		2242	64.8	3.8	105	20.0	6.3

The results presented in Figure 4.2.1 indicated that the A/C ratio was an important parameter which governed the compressive strength. In the first four series of this section, it was found that the compressive strength was inversely proportional to the A/C ratio. It can also be noted that the difference in strength between each series when the A/C ratios were 3 and 6 was less compared to that when the A/C ratio was 4. The difference could be explained by the different contributions of aggregate strength, bonding strength and the strength of the cement matrix to the overall strength of the block. With the A/C ratio was as low as 3, the cement matrix was more dominant and the strength of the blocks was mainly depended on the strength of the cement matrix. .

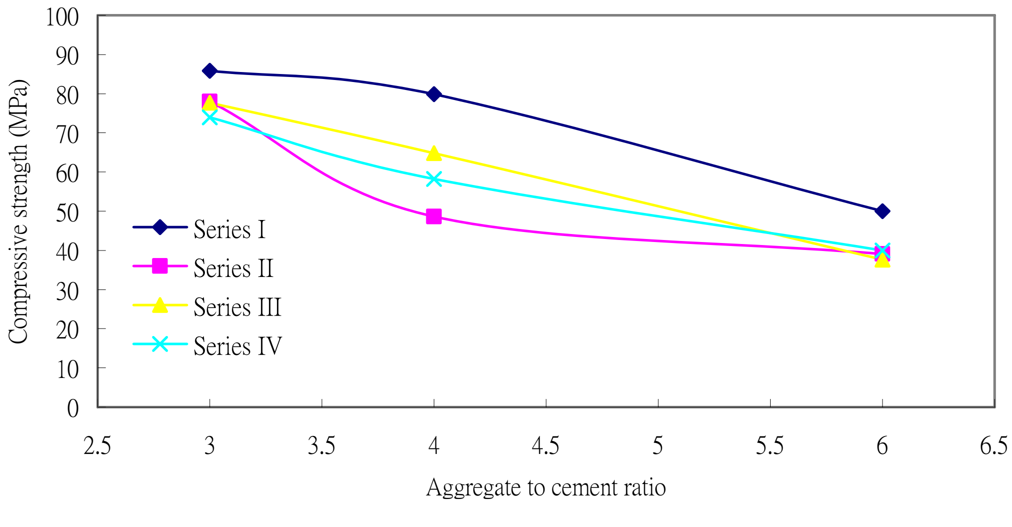


Figure 4.2.1 – Relationship between strength and A/C ratio for concrete mixtures in Series I, II, III and IV

When the A/C ratio was increased to 4, the difference in strength between the blocks prepared with different type of aggregates became significant. It was found that the block strength was directly proportional to the corresponding aggregates strength as shown in Figure 4.2.2 which used 10 % fines value as an indication of the crushing strength of the aggregate.

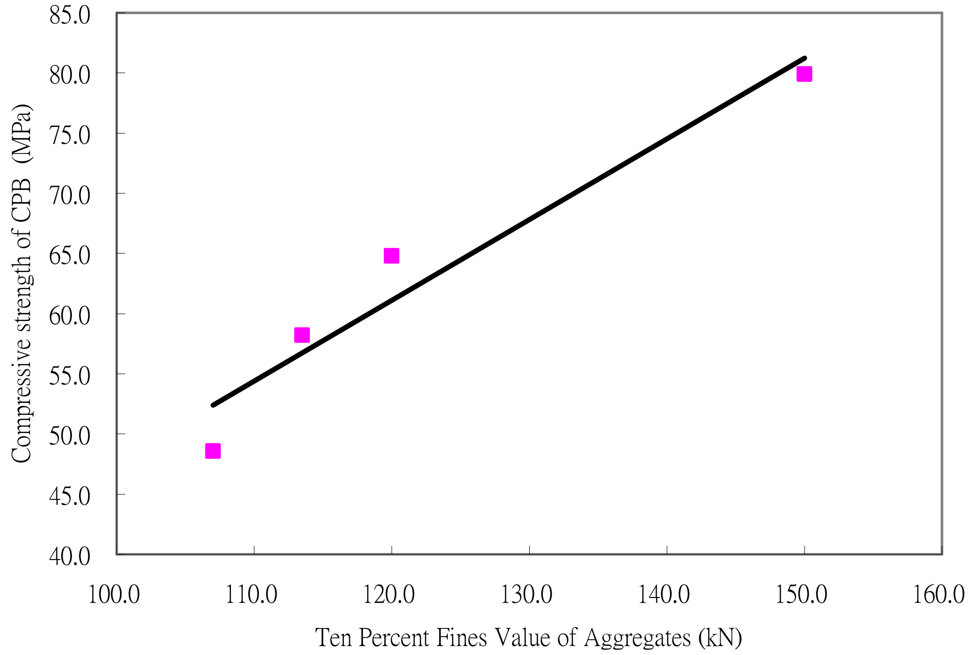


Figure 4.2.2 – Relationship between strength and ten percent fines value of concrete mixtures prepared with A/C ratio of 4 in Series I, II, III and IV

But when the A/C ratio was further increased to 6, it was believed that the bonding between the cement matrix and the RFA and RCG became relatively weak, thus rendering a lower strength. But the strength of the blocks prepared with the NFA was still the highest due to probably a better intrinsic strength of NFA.

A simple binomial relationship can be used to estimate the strength of blocks prepared with RFA with different A/C ratios ranging from 3 to 13 as shown in Figure 4.2.3.

$F_c = 0.56(A/C)^2 - 14.96(A/C) + 116.13$; for 3<A/C<13

F_c = Compressive strength

(A/C) = Aggregate to cement ratio

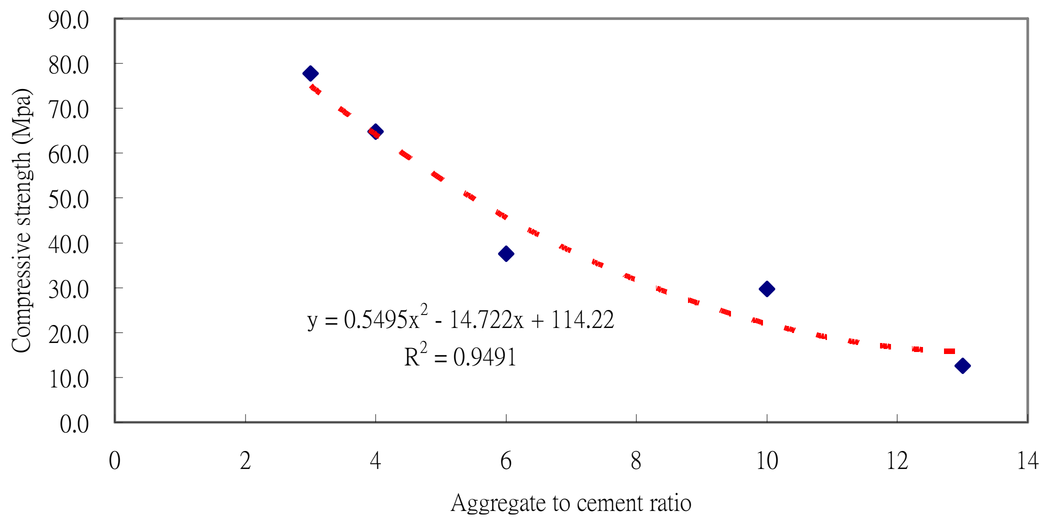


Figure 4.2.3– Relationship between strength and A/C ratio for concrete mixtures in Series III

As mentioned before, it was believed that the aggregate strength (i.e. crushing strength) also affected the compressive strength of the blocks. It was found that the compressive strength of blocks prepared with 50 % RCA and 50 % RCG was approximately the average of those prepared with only one type of aggregate (i.e. RFA or RCG). To further study the effects of aggregate strength on the compressive strength of blocks, NFA was partially or entirely replaced by RFA in the concrete mixtures in Series V. The results indicated that the use of RFA lowered the compressive strength (Figure 4.2.4). In Series VI, the incorporation of RCG as a replacement of RFA also reduced the compressive strength of blocks as shown in Figure 4.2.5. These results demonstrated the importance of aggregate strength in the development of the mechanical strength of the blocks.

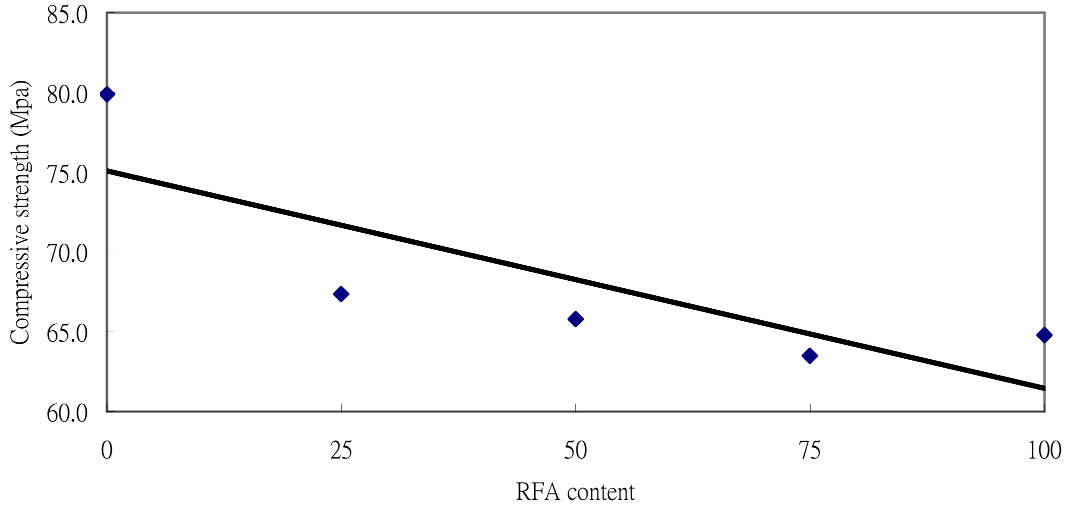


Figure 4.2.4- Relationship between 28-day compressive strengths and NFA content.

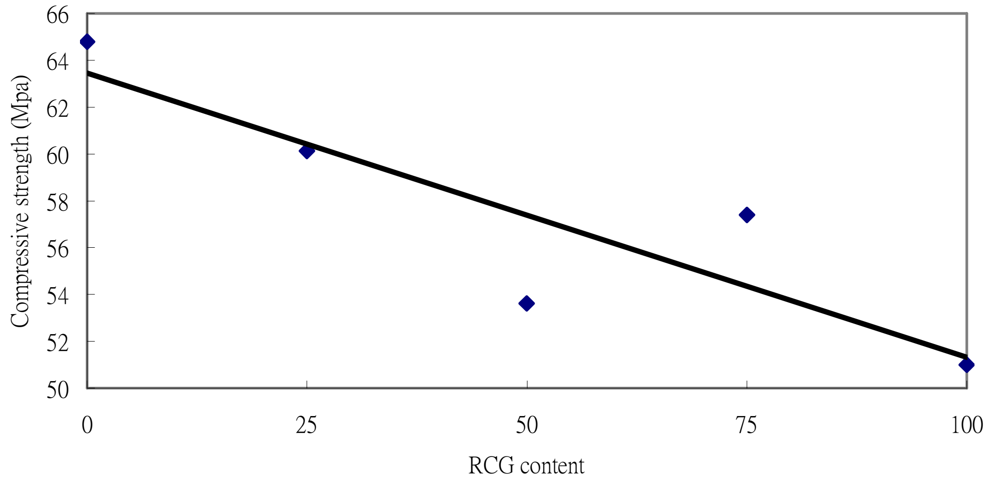


Figure 4.2.5 - Relationship between 28-day compressive strengths and RCG content.

The results were further illustrated by plotting the compressive strengths of the blocks in Series V and Series VI against the ten percent fines values of the blend aggregates as shown in Figure 4.2.6. It was found that the compressive strength of the blocks had a good correlation with the ten percent fines values of the blend aggregates. This result was consistent with those of the previous study [Poon *et al*., 2005]. Nevertheless, all the specimens tested in this study fulfilled the minimum compressive strength requirements prescribed by ETWB of Hong Kong for Grade A and B paving block for pedestrian areas [ETWB, 2004] (Table 2.6.2).

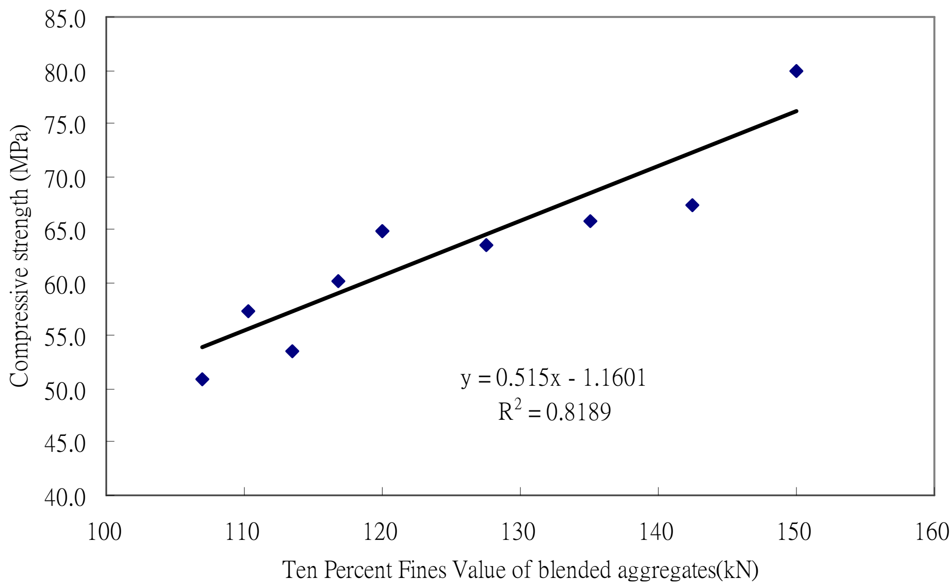


Figure 4.2.6 - Relationship between 28-day compressive strengths and ten percent fines values of blended aggregates

4.3 The effects of A/C ratios and types of aggregates on density

The results of the density measurements in Series I to VI are shown in Figure 4.3.1. It was found that the density of the blocks reduced as the A/C ratio increased as shown in Figure . This phenomenon could be attributed to 1) the density of cement (~3,150kg/m^3) was higher than that of the aggregates. Therefore, the density of paving blocks was affected by the ratio of cement to aggregate in the block, and 2) cement, a very fine powder, could easily fill up the voids between the aggregates, thus increasing the density of block.

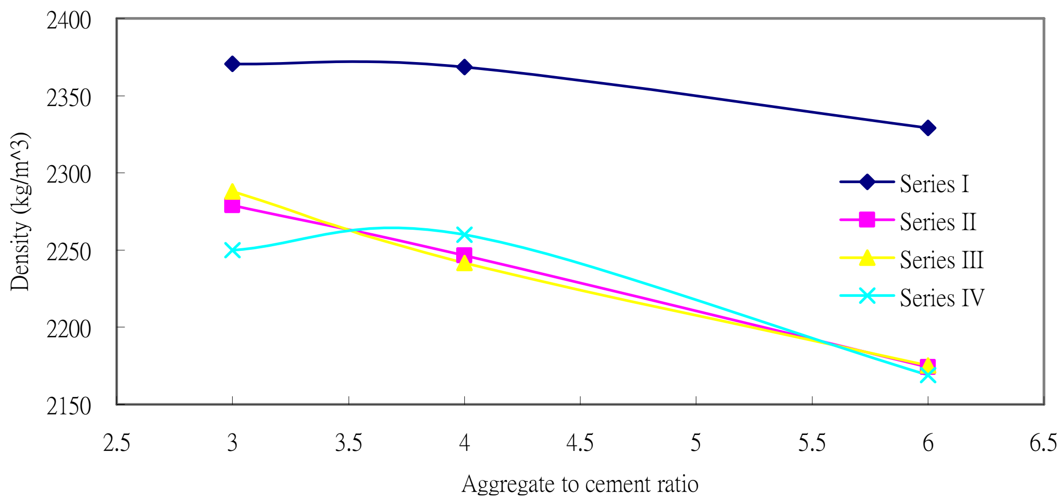


Figure 4.3.1 - Relationship between density and A/C ratio.

On the other hand, the results also showed the density of the blocks was affected by the particle density of the aggregate. Figure 4.3.2 shows that the increasing use of NFA increased the density of the blocks in Series V. The result was expected because NFA had a higher particle density compared to that of RFA. However, the change in the density of the blocks was not significant in Series VI when RCG was used as a replacement of RFA (Figure 4.3.3). This was attributed to the similar particle densities between RFA and RCG.

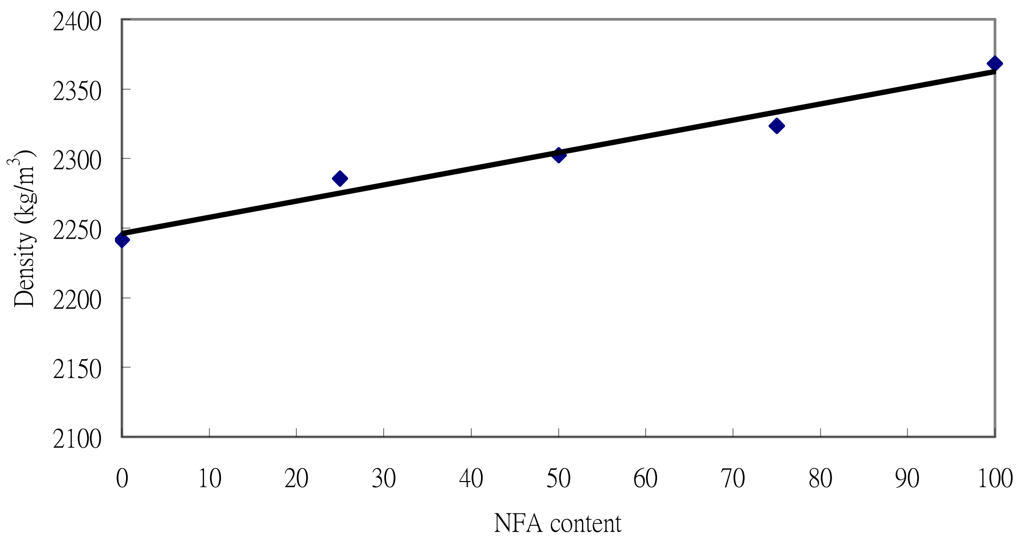


Figure 4.3.2 - Relationship between density and NFA content in Series V

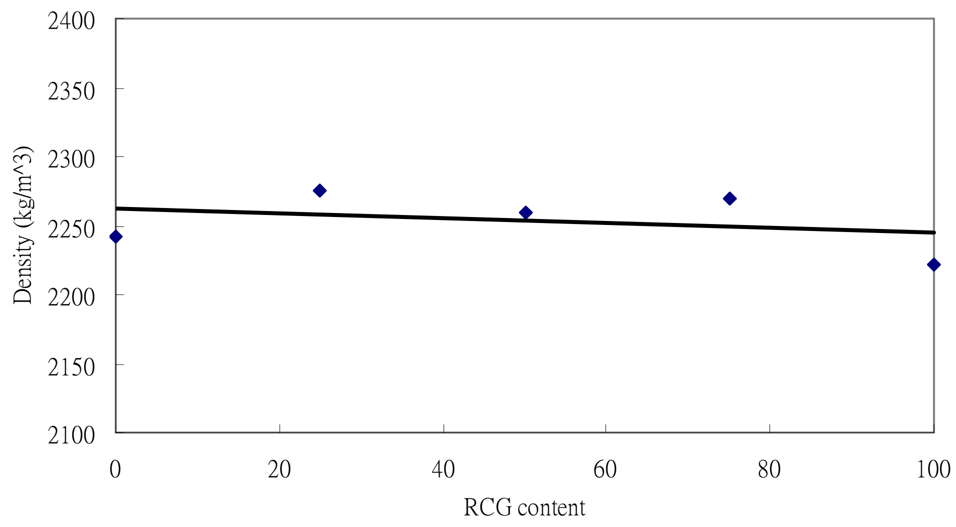


Figure 4.3.3 - Relationship between density and RCG content in Series VI

4.4 The effects of A/C ratios and types of aggregates on water absorption

The magnitude of water absorption increased as the A/C ratio increased as shown in Figure 4.4.1. When the A/C ratio was low, cement grains could fill up the pores, thus reducing the water absorption. In addition, the water absorption of the aggregates also played an important role in determining the water absorption of the blocks.

Figure 4.4.2 and 4.4.3 show that the use of aggregates, with low water absorbability (NFA and RCG) as a replacement of aggregate with high water absorbability (RFA), reduced the water absorption of the blocks significantly.

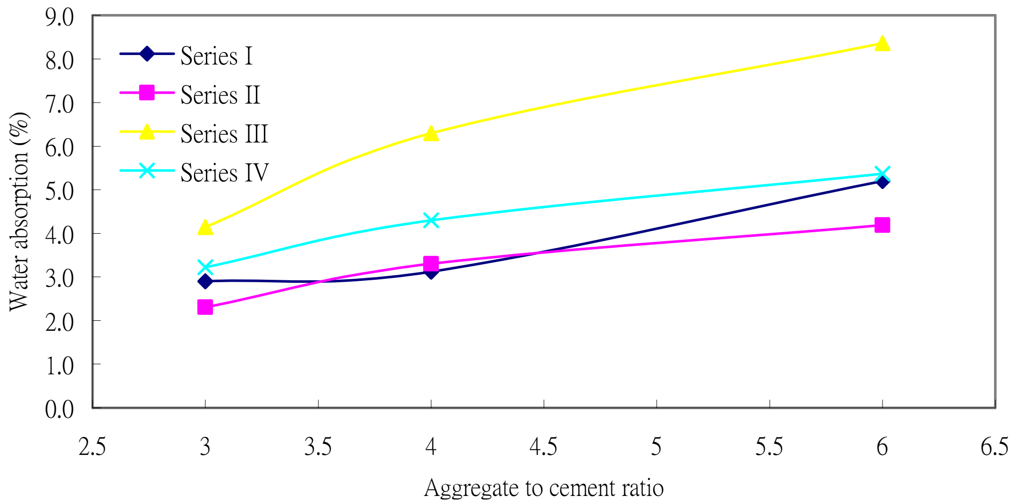


Figure 4.4.1 - Relationship between water absorption values and A/C ratio

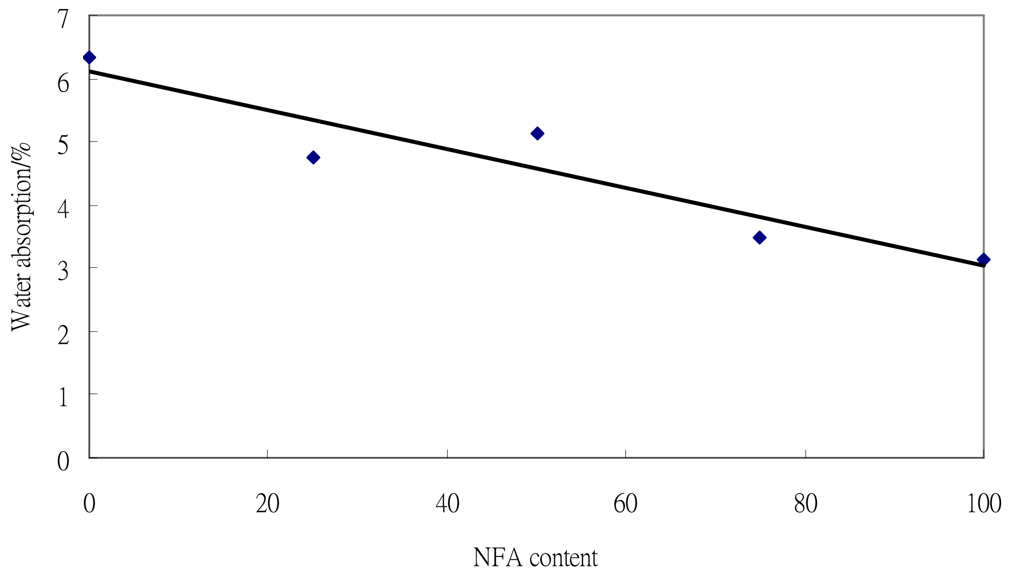


Figure 4.4.2 - Relationship between water absorption values and NCA content in Series V

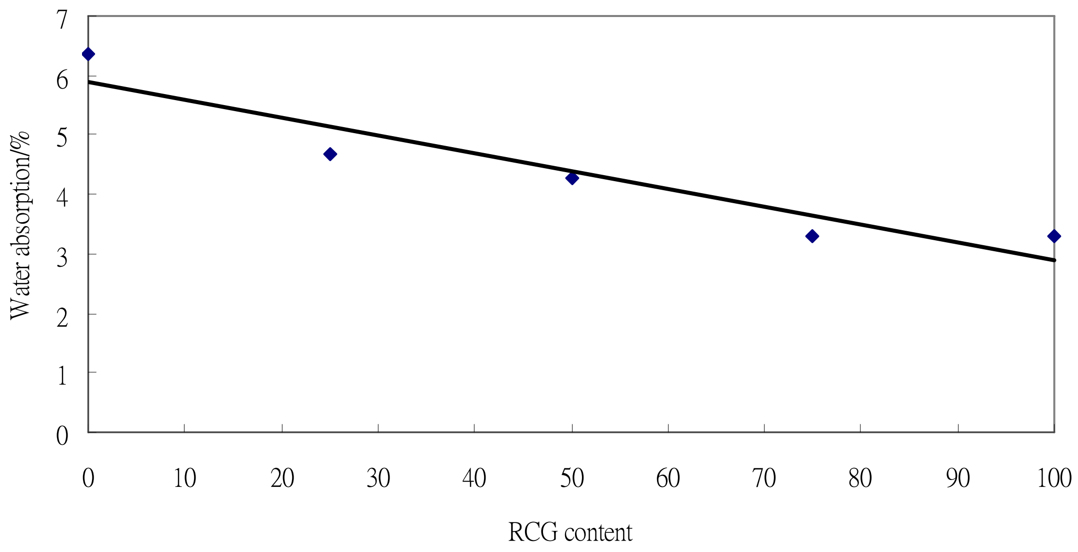


Figure 4.4.3 - Relationship between water absorption values and RCG content in Series VI

The water absorption values of the blocks produced in Series V and VI are plotted against the water absorption of the corresponding blended aggregates as shown in Figure 4.4.4. An expected trend was observed which showed that the water absorption value of the blocks was directly proportional to the water absorption of the corresponding blended aggregates.

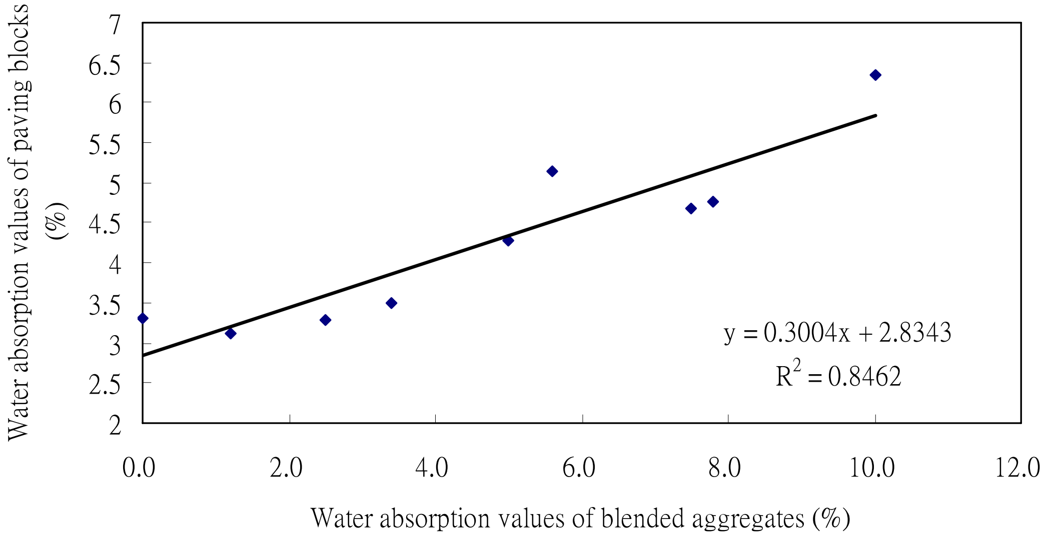


Figure 4.4.4 Relationship between water absorption values of blocks and water absorption of the corresponding blended aggregates

In practice, it is found that the block prepared with 100% RFA did not meet the water absorption requirements prescribed by ETWB of Hong Kong for Grade A paving blocks which have a cold water absorption limit of 6%. However, when RCG was used as a 25% replacement of RFA, the water absorption of the blocks could be controlled to within 6%. However, an alternative way to reduce the water absorption value of the blocks was to decrease the A/C ratio to less than 4.

Although the use of RCG in paving blocks can compensate the high water absorption of

RCA, the durability of the paving blocks is still a concern. The glass cullet would react with alkali in cement to form a type of gel, the alkaline-silica-gel, that may reduce the durability of the blocks. Section 6 will report on the results on the possible ASR gel formation in block and ways to control the deleterious reaction.

4.5 The effects of A/C ratios and types of aggregates on skid and abrasion resistances

When the blocks are used for paving application, skid resistance and abrasion resistance are important. The results of skid resistance and abrasion resistance are shown in Table 4.2.1. All the specimens tested in Series I to VI were able to satisfy relevant standards with respect to skid resistance. In Series I to IV, the skid resistance of all the specimens prepared with an A/C ratio of 3 were slightly lower than the other specimens prepared with A/C ratios of 4 and 6. This was mainly due to the surface texture of blocks being smoother with an increasing cement content. However, the nature of the aggregates used did not have a significant effect on the skid resistance results since the aggregates, in most cases, were embedded in the cement matrix.

The results of the abrasion resistance showed that paving blocks prepared with A/C ratios of 3 and 4 exhibited satisfactory performance (<23mm). But the abrasion resistance of the specimens prepared with an A/C ratio of 6 was only marginal. This was because in those specimens, the cement content was not sufficient to firmly bind the aggregate. This result also agrees with others that the ability of concrete to withstand abrasion improves with an increase in the concrete strength [Mindess *et al*., 2003].

4.6 Summary

In Chapter 4, the factors affecting the properties of concrete blocks were investigated and the results can be summarized as follows:

1. The compressive strength increased with a decrease in A/C ratio.
2. The compressive strength was directly proportional to strength of the blended aggregate.
3. The blocks prepared with 100% RCA could not meet the requirements of water absorption unless the A/C ratio was decreased to 3.
4. The use of NFA or RCG as a replacement of RFA reduced the water absorption of the blocks .
5. The water absorption of the blocks was closely related to the water absorbability of the aggregate particles.
6. The abrasion resistance and skid resistance of the blocks were affected by the A/C ratio. When the A/C ratio was larger than 4 the abrasion resistance was marginal. However, there was no direct relationship between the aggregate types and the abrasion or skid resistance of the blocks.
7. To make use of recycled materials to produce eco-friendly (100% recycled materials as aggregates) paving blocks with good quality, it is recommended to prepare the

blocks with 50% Recycled crushed glass (RCG) and 50% recycled fine aggregate (RFA) and with an A/C ratio 4 or below.

Chapter 5 The Effect of Aggregate Grading on the Engineering Properties of Concrete Blocks

5.1 Introduction

Previous sections have shown that recycled aggregates derived from construction and demolition (C&D) wastes can be used for the production of concrete blocks. However, the use of recycled aggregates would cause a reduction in the compressive strength and dimensional stability of the blocks. Although using additional amount of cement can compensate this drawback, the production cost would be increased. Alternatively, the grading of the aggregates can be controlled and adjusted to a level at which the properties of the blocks are optimized.

In this section, a study on finding the grading curve, appropriate fineness modulus (FM) and packing density of blended different types and amounts of natural and recycled aggregates for optimizing the production of concrete blocks is reported. The results show that the ideal aggregate grading curve for strength maximization should has a finesses modulus value of 3.7 and a packing density of 0.738. Furthermore, the change in the fineness modulus and packing density would affect the density, water absorption, skid and abrasion resistances of the produced blocks. It was found that aggregates with a FM value ranging from 3.5 to 4.5 was most suitable for concrete block production. Moreover, the compressive strength, density, water absorption and abrasion resistance basically improved as the packing density increased.

5.2 Ideal grading curve:

The compressive strength of the concrete blocks in Series VII is shown in Figure 5.2.1. The compressive strength increased as the amount of fine aggregate increased in the mix proportions. The ideal grading curve Figure 5.2.2 is defined as the grading of aggregates which leads to the highest compressive strength. When all six classes of aggregates were used, the compressive strength reached the highest. Also, It was found that the grading of the ideal grading curve derived from the experiment lied between the ideal grading curves proposed by Fuller and Thompson [1907], with q being equal to 0.2 and 0.4 (Eq2.1).

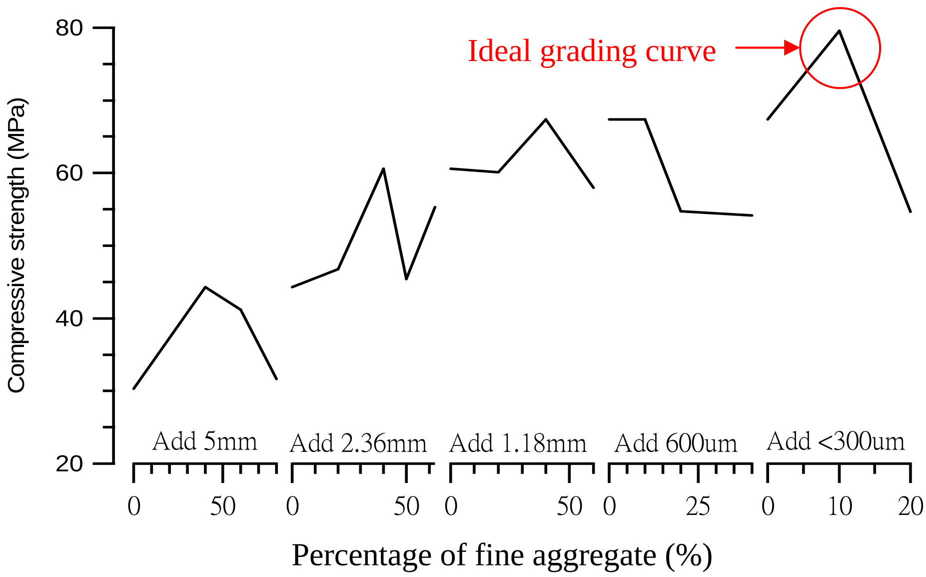


Figure 5.2.1 Compressive strength of concrete blocks prepared with different aggregate grading

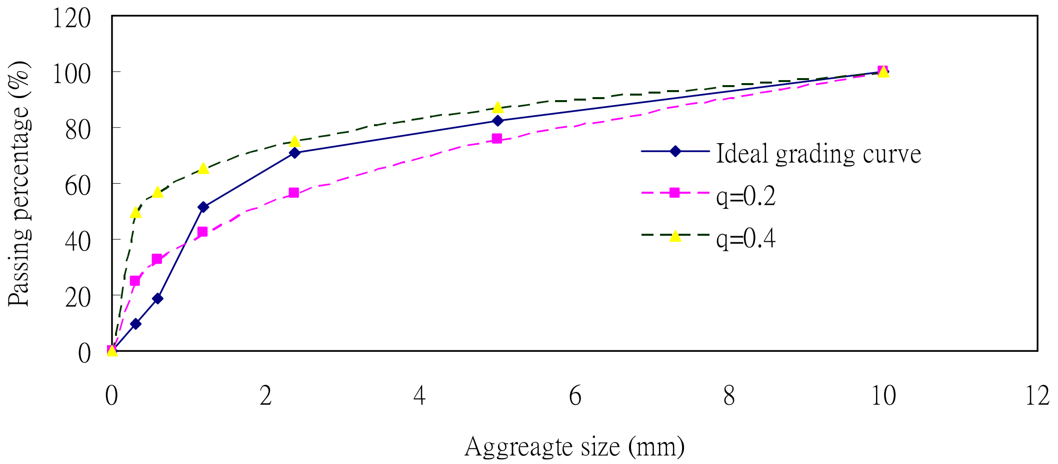


Figure 5.2.2 Comparison between ideal grading curve used in this study and those proposed by Fuller

The results also revealed that the properties of the produced blocks were affected by the grading of aggregates. As more fine particles were added into the mixes, the voids were filled more effectively and the density was higher Figure 5.2.3. Correspondingly the water absorption Figure 5.2.4 was reduced and the abrasion resistance Figure 5.2.5 was increased as the amount of fine particles increased. However, it was interesting to note that the skid resistance Figure 5.2.6 reduced as more fine particles were added into the mix. This could be attributed to the change of block surface from a rough to a smooth and dense texture as more fine particles were added, thus reducing the skid resistance.

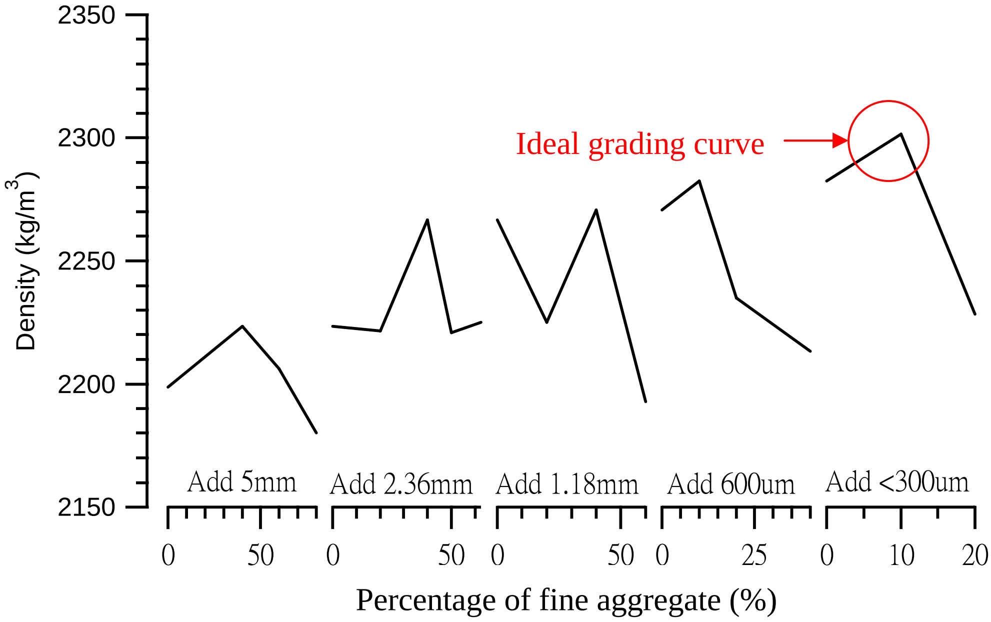


Figure 5.2.3 – Density of concrete blocks prepared with different aggregate grading

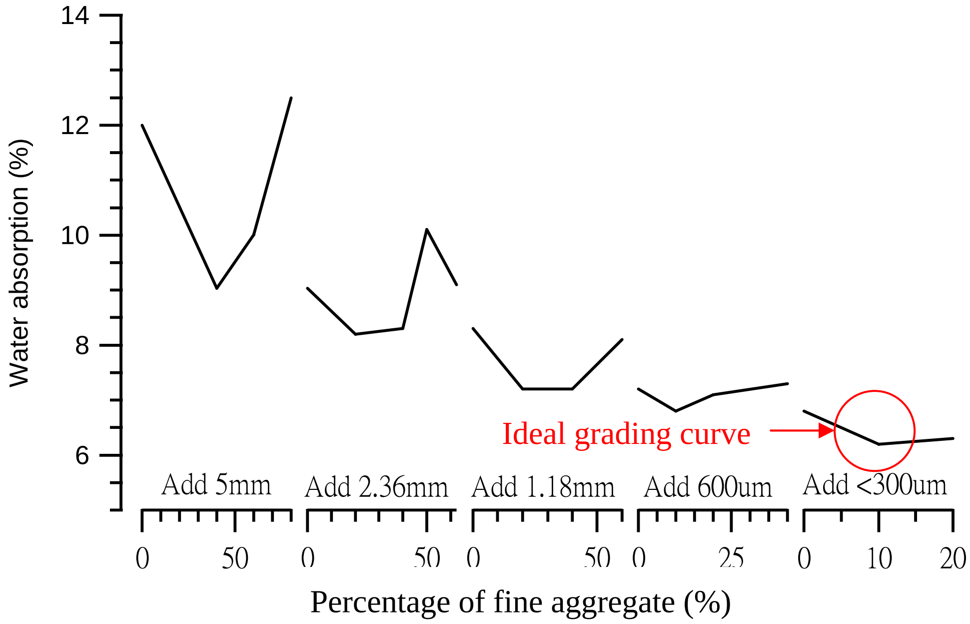


Figure 5.2.4 Water absorption of concrete blocks prepared with different aggregate grading

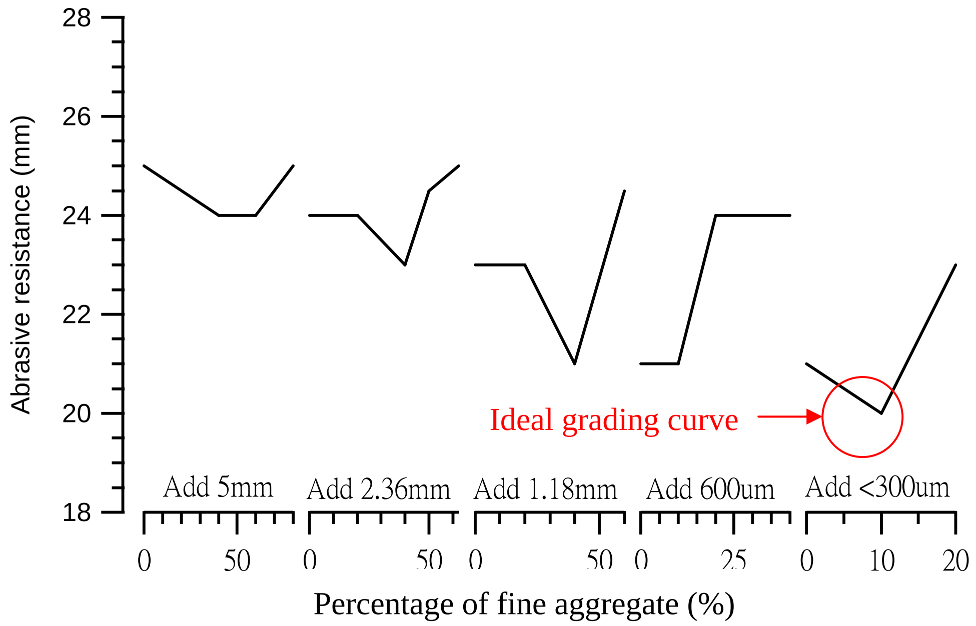


Figure 5.2.5 Abrasion resistance of concrete blocks prepared with different aggregate grading

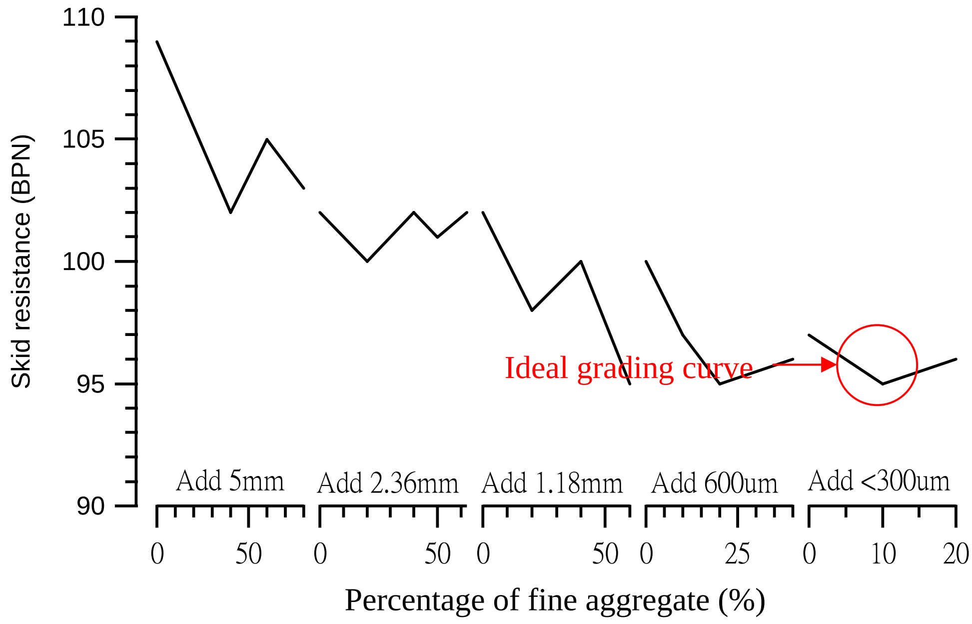


Figure 5.2.6 Skid resistance of concrete blocks prepared with different aggregate grading

5.3 Fineness modulus (FM):

The relationship between the compressive strength and the aggregate FM values of the mixes is shown in Figure 5.3.1. The results of Series VIII to X show a similar trend. The compressive strength of concrete block increased gradually as the FM value increased until the optimum was reached. Thereafter, the strength gradually reduced. The results indicated that an aggregate FM value ranging from 3.5 to 4.5 was a suitable range for block production. This finding, could be explained by the path of load transfer, aggregate interlocking and void content. A low FM value represents the presence of a high volume of fine materials which cannot efficiently transfer the load from the top to the bottom layer (Figure 5.3.2). Also, aggregates with a low FM value do not provide sufficient interlocking in the concrete blocks.

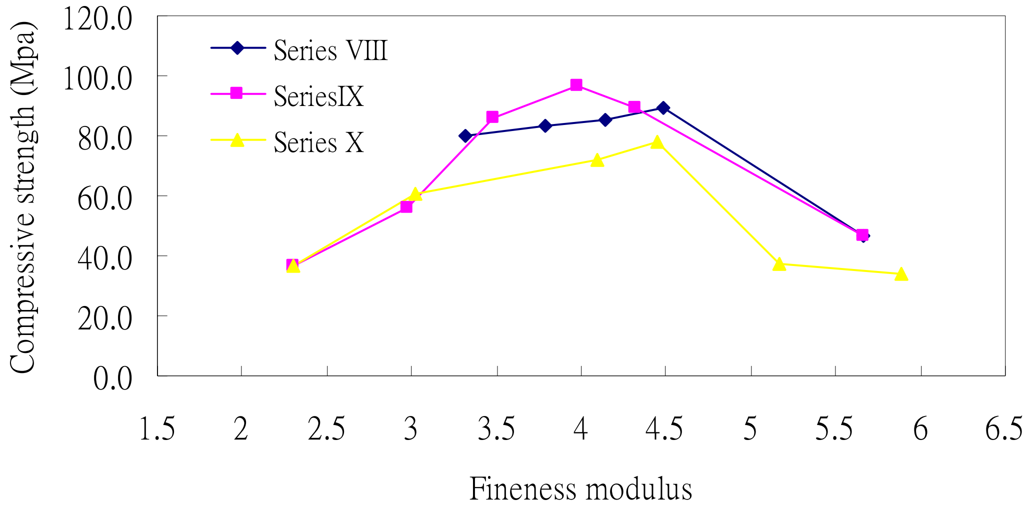


Figure 5.3.1 Relationship between compressive strength and fineness modulus for concrete mixtures in Series VIII-X

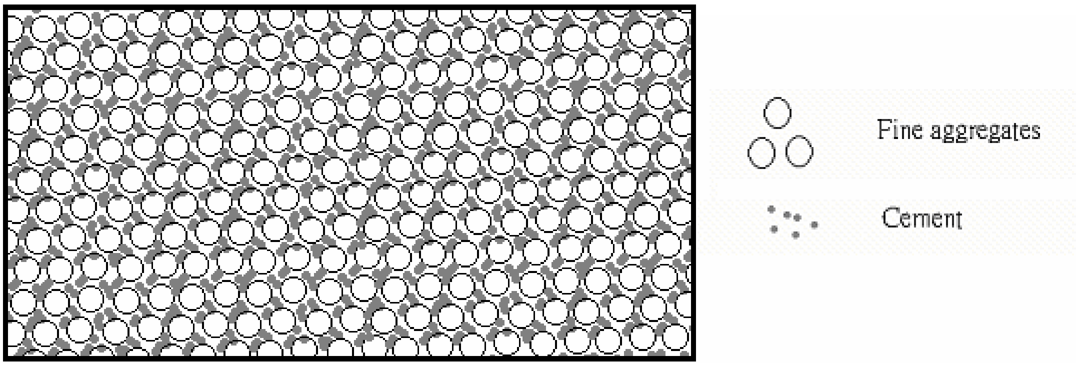


Figure 5.3.2 Structure of concrete block prepared with fine aggregate

In contrast, aggregates with most particles are of larger sizes (high FM) would reduce the overall specific surface area for effective load distribution (Figure 5.3.3), thus reducing the strength of the blocks.

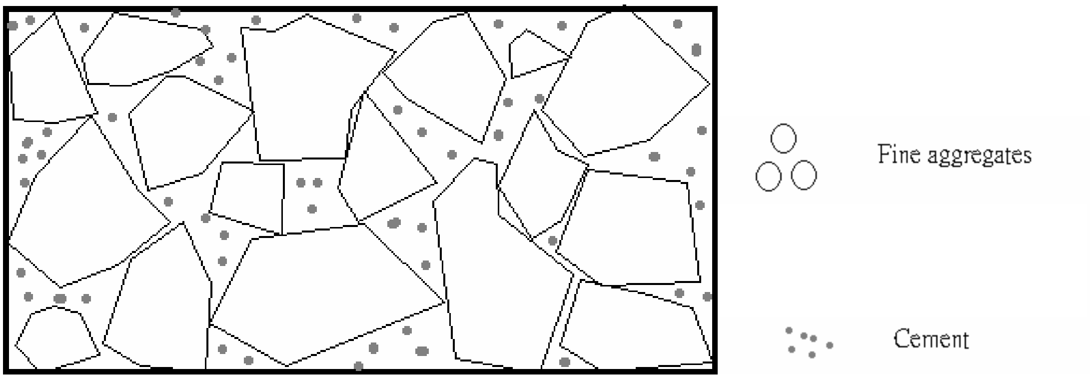


Figure 5.3.3 Structure of concrete block prepared with coarse aggregate

Therefore, concrete blocks with higher compressive strength could only be produced when the coarse aggregate and fine aggregate were at a suitable proportion like Figure 5.3.4. The results of this study indicated that the FM value of the blended aggregate ranging from 3.5 to 4.5 was suitable to make concrete blocks with optimal strength. Furthermore, it was found that the FM value of the ideal grading curve in Series VII was about 3.7 which is consistent with the above finding.

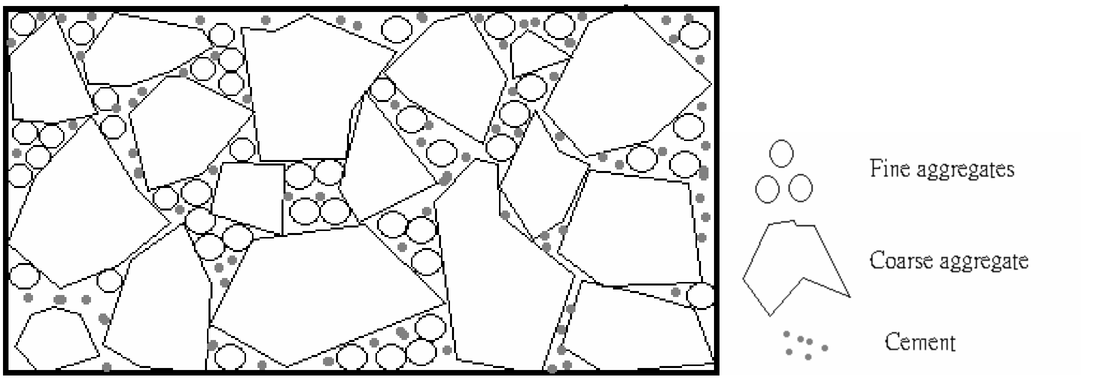


Figure 5.3.4 Structure of concrete block prepared with appropriated grading aggregate

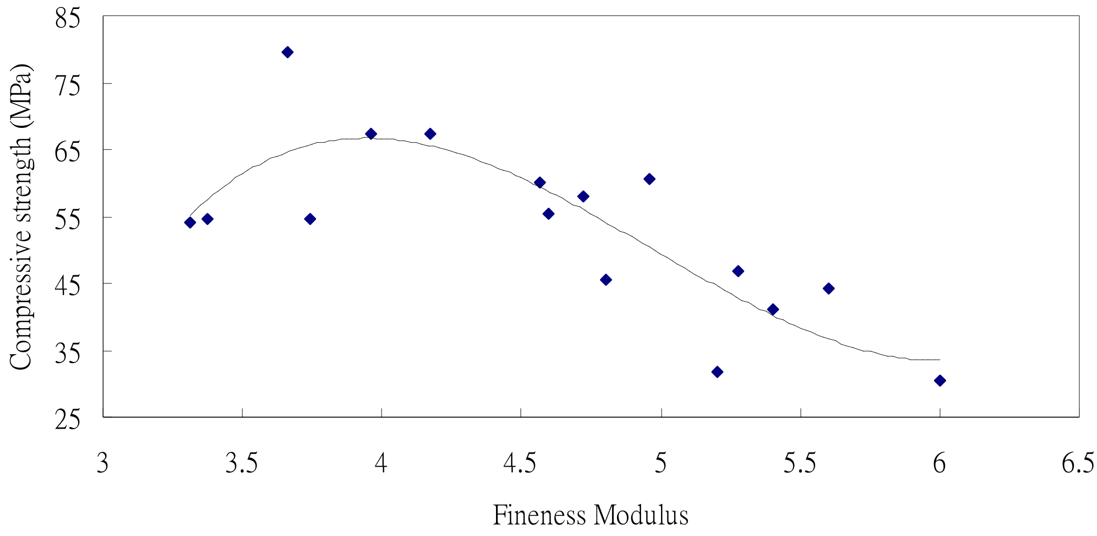


Figure 5.3.5 Relationship between the compressive strength and fineness modulus for concrete mixtures in Series VII.

In addition, the density of the concrete paving blocks varied significantly when the FM value was altered. As shown in Figure 5.3.6, the density of the concrete blocks was maximized when FM was between 3.5 and 4.5. On the other hand, Figure 5.3.7 shows that the water absorption increased significantly as the FM value extended beyond 4.5. It can be attributed to the high coarse aggregates content in the mix which created large volumes of voids. ;

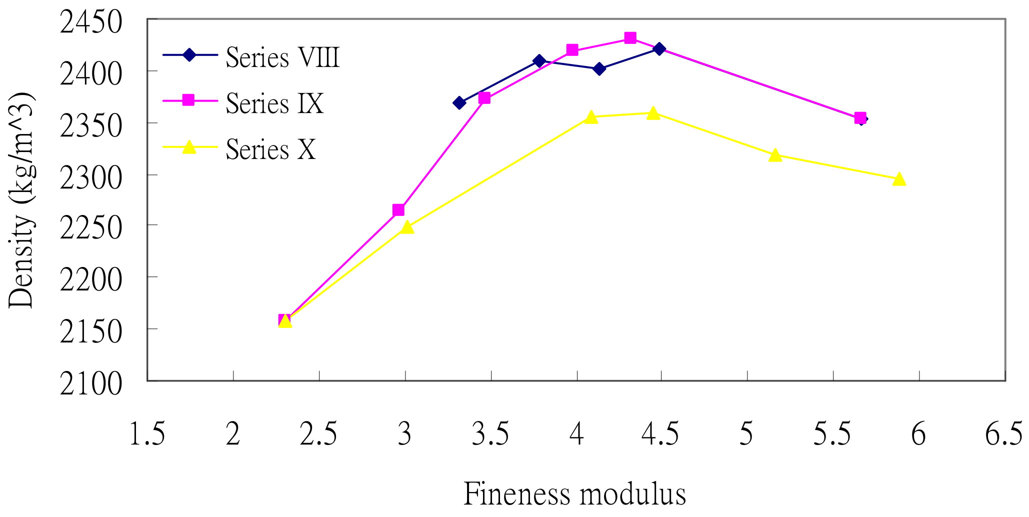


Figure 5.3.6 Relationship between compressive strength and fineness modulus for concrete mixtures in Series VIII-X.

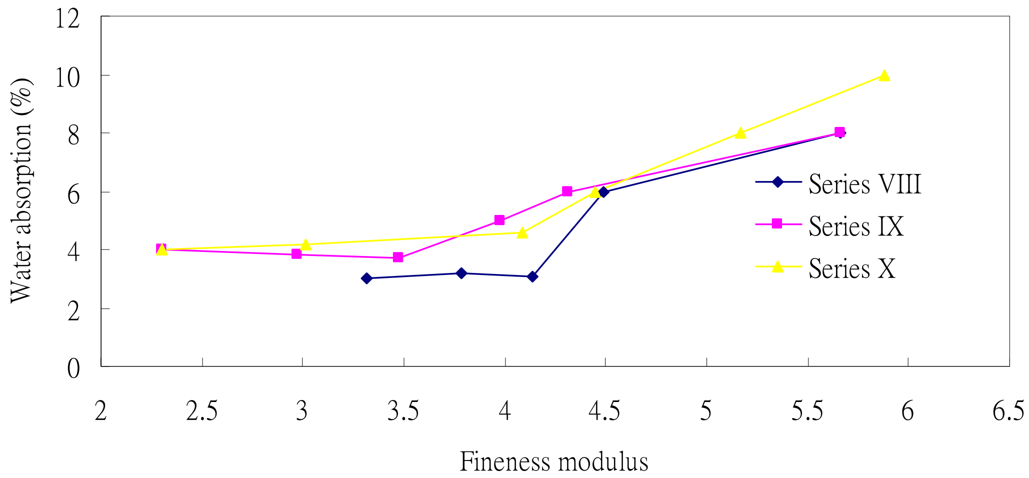


Figure 5.3.7 Relationship between the water absorption and fineness modulus for concrete mixtures in Series VIII-X.

A summary of the skid resistance and abrasion resistance of the concrete mixtures is shown in Table 5.3.1. The results show that the FM value affected the skid resistance of the concrete block significantly. It was found that the skid resistance increased as the

FM value increased as the increasing use of coarse aggregate would form a porous and rough surface which increased the skid resistance. On the other hand, the concrete blocks possessed a low abrasion resistance when the FM value was either too high or too low. As mentioned before, when FM was too high, there were not enough aggregate particles to resist the abrasive action. In contrast, when the FM was too low, the fine particles were not strong enough to withstand the abrasive action. Therefore, the ability of the blocks to resist the abrasive action would be poor in both extreme cases. Moreover, it was found that the types of the aggregates were not a significant factor in affecting the range of FM which was considered optimum for block production.

Table 5.3.1 Results of FM, packing density, skid resistance and abrasive resistance

Notations	Fineness Modulus	Packing density	Skid resistance (BPN)	Abrasion resistance (mm)
Series I				
I-5-1	6	0.580	109	25
I-5-2	5.6	0.634	102	24
I-5-3	5.4	0.622	105	24
I-5-4	5.2	0.600	103	25
I-236-1	5.3	0.668	100	24
I-236-2	5.0	0.665	102	23
I-236-3	4.8	0.650	101	25
I-236-4	4.6	0.627	102	25
I-118-1	4.6	0.688	98	23
I-118-2	4.2	0.672	100	21
I-118-3		0.629	95	25
I-600-1	3.7	0.691	95	24
I-600-2	3.3	0.674	96	24
I-600-3	4.0	0.684	97	21
I-300-1	3.7	0.738	95	20
I-300-2	3.4	0.700	96	23
Series II				
NC100	5.7	0.633	110	24
NC50/NF50	4.5	0.764	95	20
NC35/NF65	4.1	0.770	95	22
NC20/NF80	3.8	0.764	96	22
NF100	3.3	0.751	90	25
Series III				
S100	2.3	0.659	92	24
NC20S80	3.0	0.699	95	21
NC35S65	3.5	0.727	94	20
NC50S50	4.0	0.755	95	20
NC60S40	4.3	0.736	98	20
Series IV				
RC100	5.9	0.633	115	25
RC80S20	5.2	0.645	110	26
RC60S40	4.4	0.722	95	20
RC50S50	4.1	0.712	94	21
RC20S80	3.0	0.690	90	20

5.4 Packing density

The packing density of the mixtures in Series VIII to X was predicted by the computer program. As expected, Figure 5.4.1 and 5.4.2 show that the compressive strength and density increased when the packing density increased.

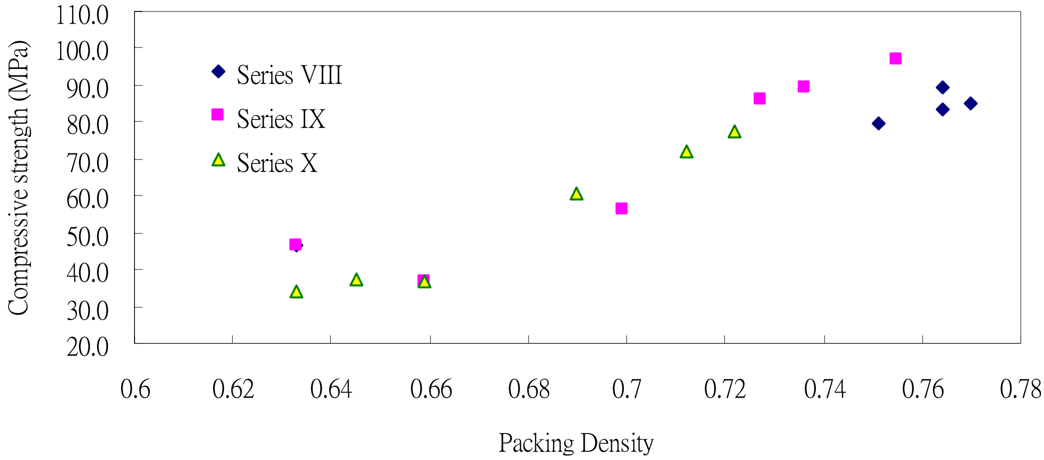


Figure 5.4.1 Relationship between the compressive strength and packing density for concrete mixtures in Series VIII-X

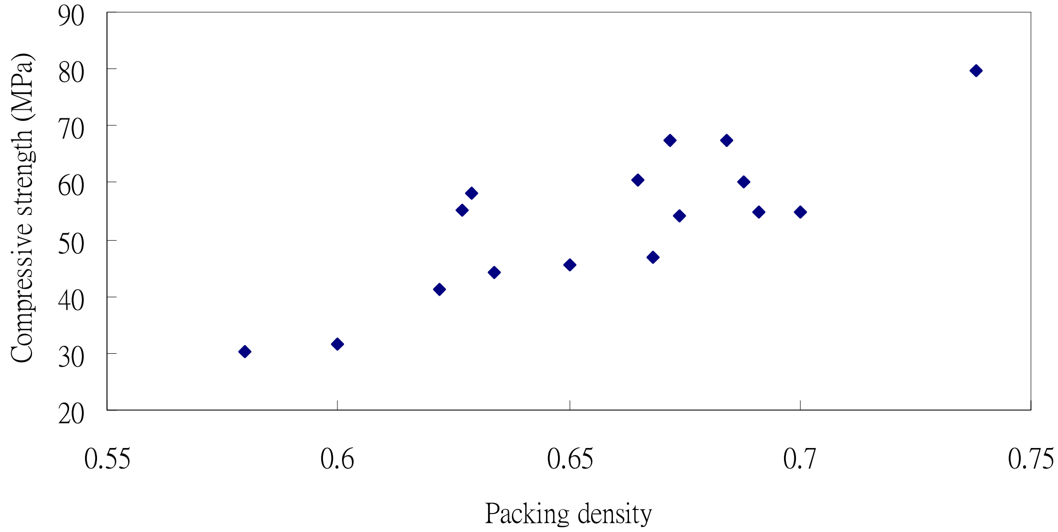


Figure 5.4.2 Relationship between the compressive strength and packing density for concrete mixture in Series VII

Furthermore, Figure 5.4.3 and 5.4.4 shows that the water absorption decreased with an increase in the packing density. This can be attributed to the decreasing void content when packing density increased. The results in Figure 5.3.1 also indicate that the skid resistance decreased and the abrasion resistance increased with the increase in packing density. For the same cement content, smooth surface and better appearance of concrete block could be achieved by increasing the packing density since more cement mortar would form on the surface of the blocks when less cement was needed to fill the voids within the blocks. Furthermore, the high strength as a result of the high packing density led to an increase in the abrasion resistance.

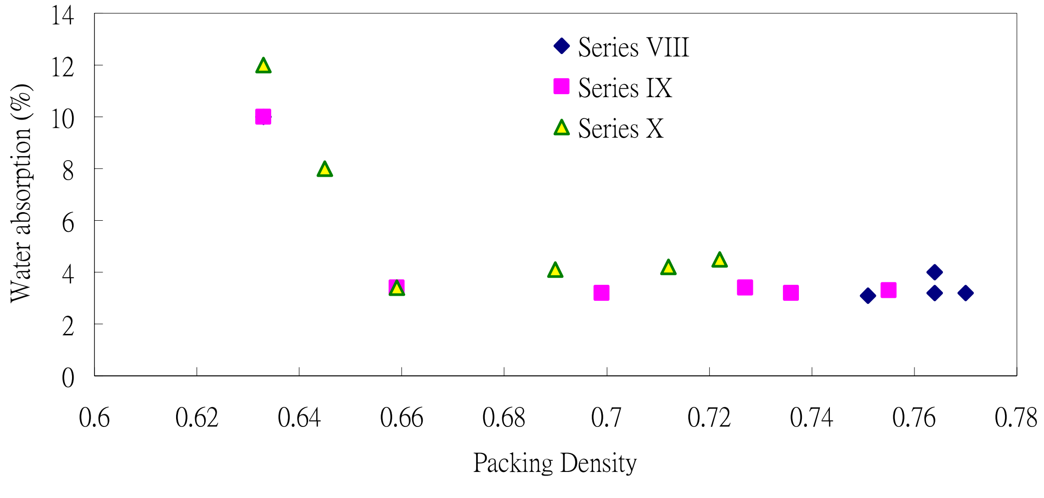


Figure 5.4.3 Relationship between the water absorption and packing density for concrete mixtures in Series VIII-X.

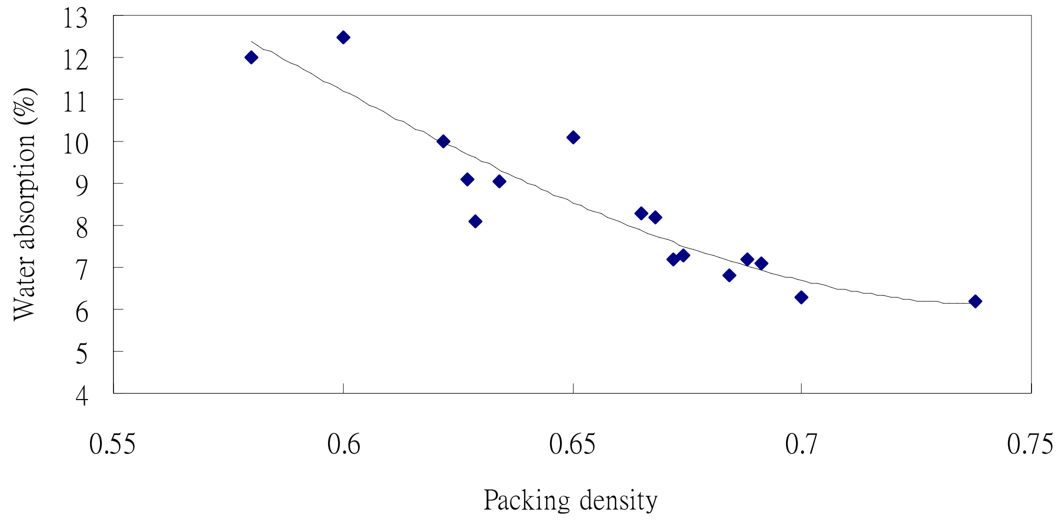


Figure 5.4.4 Relationship between the water absorption and packing density for concrete mixture in Series VII.

5.5 Comparison between FM, packing density value and ideal grading curve

The weakness of the ideal grading approach was that it was rarely possible to replicate exactly the ideal grading in the aggregate mixtures. However, if the quality control of the crushing aggregates and the combination of different aggregates was appropriate, it was possible to produce aggregates close to the ideal grading. The FM value and packing density of aggregate of ideal grading curve were 3.7 and 0.738 respectively. Both FM value and packing density indicated that the aggregate mixtures with ideal grading curve possessed a low void content of aggregate mixture.

Although the packing density approach was more reliable and scientific when comparing with the ideal grading curve, this approach consisted of a very complicated calculation process and calibration and it is impossible to calculate the packing density without using a computer program.

Although the FM approach was simple, it was found that the best mechanical properties were achieved when the FM value was between 3.5 and 4.5. To further explain this finding, the packing density was plotted against the fineness modulus in Figures 5.4.1 and 5.4.2. Generally, high packing density was achieved when the FM value was between 3.5 and 4.5. It was suggested that that the FM value and the packing density of aggregate should be within 3.5 and 4.5 and higher than 0.7 respectively in order to give better mechanical properties and appearance of the concrete blocks.

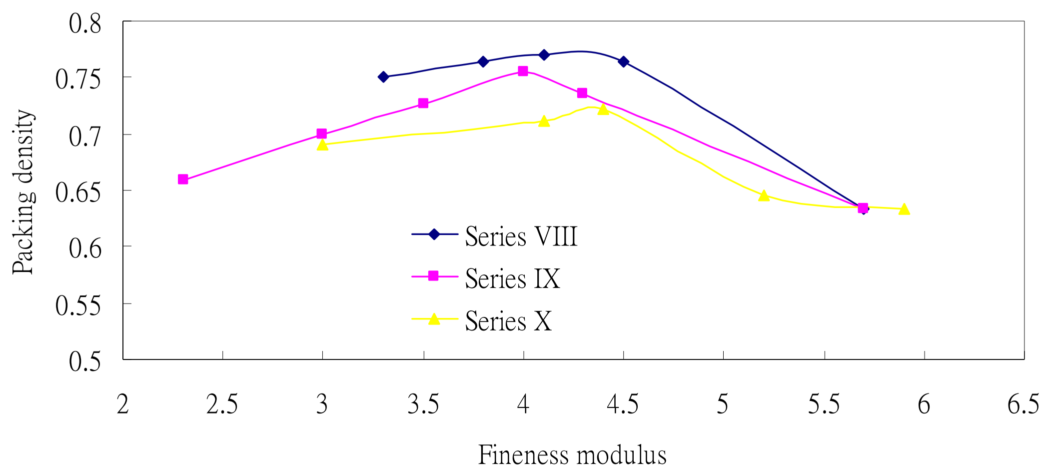


Figure 5.4.5 Relationship between the Fineness modulus and packing density for concrete mixtures in Series VIII-X

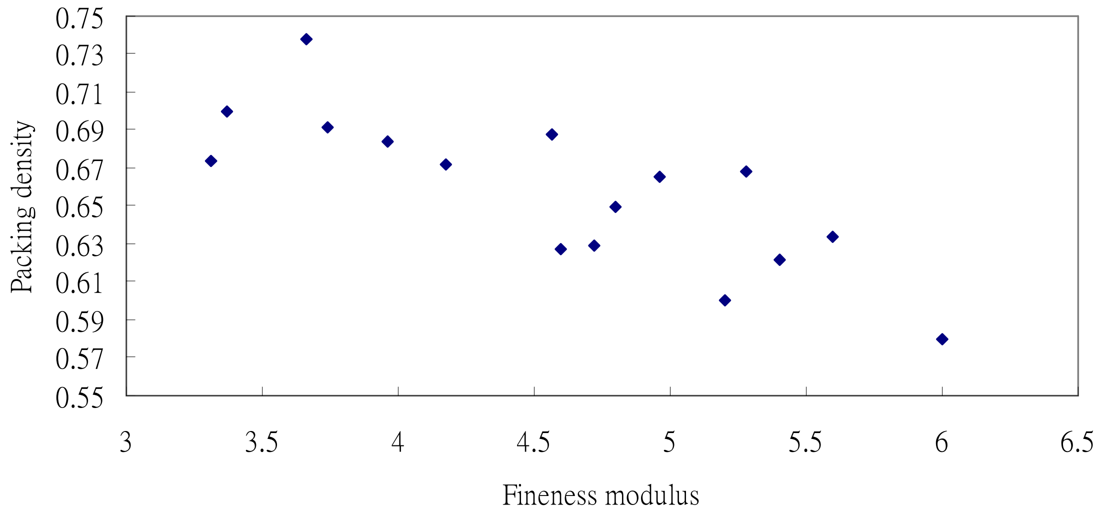


Figure 5.4.6 Relationship between the fineness modulus and packing density for concrete mixture in Series VII.

5.6 Summary

In section 5, the effect of ideal grading curve, FM and packing density on the concrete block was investigated and the results can be summarized as follows:

1. The results showed that the compressive strength, abrasion resistance and water absorption of the concrete blocks were improved when the blocks were prepared with aggregates with grading similar to the ideal grading curve.
2. The results showed that the FM value ranging from 3.5 to 4.5 was most suitable for concrete block production where the compressive strength, water absorption and abrasion resistance were the optimum.
3. The type of aggregates used did not affect the range of FM suitable for concrete block production.
4. The compressive strength, abrasion resistance and water absorption improved as the packing density increased. It was also found that a better surface texture of concrete block was obtained when the packing density of the aggregate was larger than 0.7.
5. To optimize the properties of concrete block production, the grading of the blended aggregates used should be similar to the ideal grading curve proposed in this paper. Alternatively, the FM and packing density of the blended aggregate shall range from 3.5 to 4.5 and be larger than 0.7.

Chapter 6 Durability of Concrete Blocks Prepared with Recycled Crushed Glass- ASR Consideration

6.1 Introduction

There is a growing interest of using recycled crushed glass (RCG) as aggregate in construction materials. Although the recycled crushed glass is probably to reduce the water absorption and drying shrinkage in concrete blocks due to zero water absorption of the glass, the detrimential effect of using glass due to alkali-aggregate reaction in cementious materials is a real concern. Therefore, the ASR of mortar bars was investigated. In this section, the adequate amount of Pulverised fly ash (PFA) needed to reduce the ASR expansion for different recycled crushed glass contents using the accelerated mortar bar test in accordance with ASTM C 1260 was determined.

It was found from the mortar bar test that the incorporation of 25 % or less RCG induced negligible ASR expansion after a testing period of 28 days. However, it is recommended to incorporate at least 10 % by weight of total aggregate of Pulverized fuel ash (PFA) into the concrete mixture when the RCG content exceeded 25 %.

6.2 The ASR expansion of mortar bars without suppressing agents

The results of the mortar bar test in Series I-M are shown in Figure 6.3.1 which indicate that the ASR expansion was extremely high and was not able to meet the requirements prescribed in ASTM C 1260 (<0.1% within 14 days) when the mortar bars were prepared with 100 % RCG. In addition, it was also observed that serious cracks were found on the surface of the mortar bars. Although the mortar bars prepared with 50% RCG and 50% sand were able to meet the requirements at 14 days, serious expansion and cracks was observed at 28 days. However, the expansion of the control mortar bars in which only river sand was used was minimal.

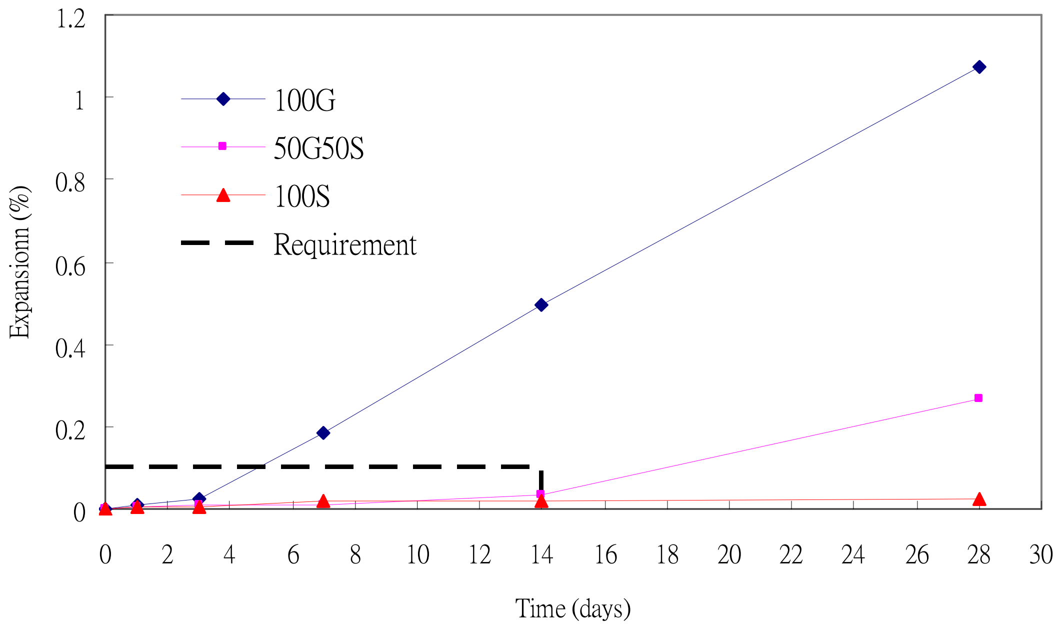


Figure 6.3.1. Results of ASR expansion of the mortar bars prepared in Series I-M

6.3 The ASR expansion of mortar bars with suppressing agents

According to previous studies, it was believed that PFA and MK were able to effectively suppress the ASR expansion. In order to assess the effect of these mineral admixtures, PFA and MK were incorporated at different percentages by weight of aggregates into the mortar bars samples prepared with 50 % RCG and 50 % sand in Series II-M and III-M respectively. The results in Figure 6.4.1 and Figure 6.3.2 show that, although all the specimens was able to comply with the ASR expansion requirements stipulated in ASTM, the suppressing ability of PFA was better than that of MK in the mortar bars with the same glass content. When considering 28-day ASR expansion, only 2.5 % PFA was able to suppress ASR expansion effectively, but 5 % MK was needed to suppress ASR expansion of the mortar bars. Therefore, the use of PFA is a better choice as an effective and economical ASR suppressant and it was used for the subsequent tests.

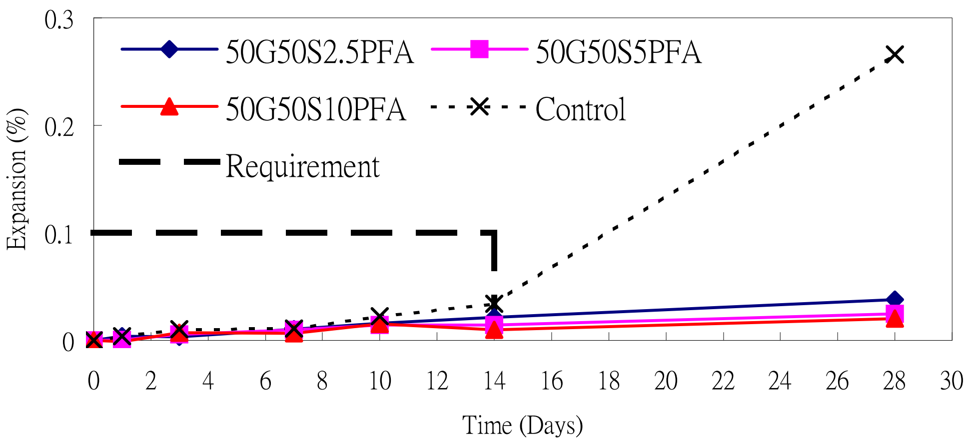


Figure 6.4.1 - Results of ASR expansion of the mortar bars prepared in Series II-M

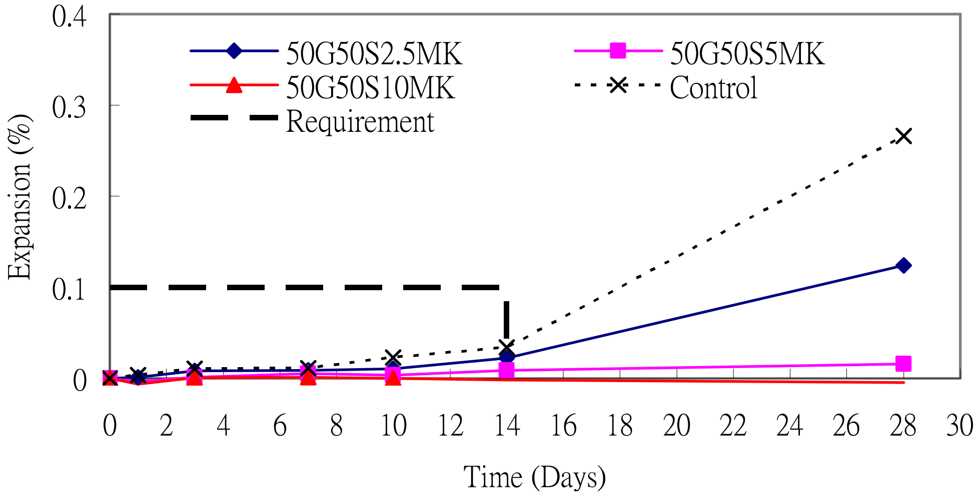


Figure 6.3.2 - Results of ASR expansion of the mortar bars prepared in Series III-M

6.4 The ASR expansion of mortar bars prepared with RCG and RFA without suppressing agents

Figure 6.4.1 shows the ASR expansion of the mortar bars prepared in Series IV-M in which natural sand was replaced by recycled fine aggregate. The results indicate that the expansion of mortar bars was not able to meet the requirements of ASR expansion when the RCG content was higher than 50 % by weight of total aggregates. However, the ASR expansion was insignificant when the RCG content was less than 25 %.

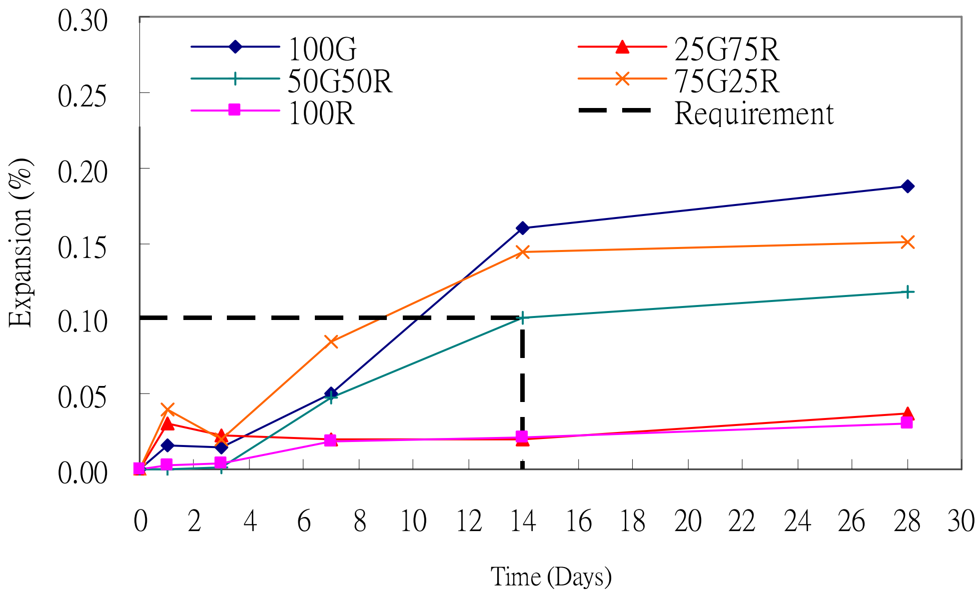


Figure 6.4.1 - Results of ASR expansion of mortar bars prepared in Series XIV

6.5 The ASR expansion of mortar bars prepared with RCG and RFA with suppressing agents

Since it was shown that PFA was an effective and economical suppressant on the ASR expansion, different percentages PFA were then incorporated into the mortar bar samples prepared with 75 %, 50 % and 25 % RCG in Series V-M, VI-M and VII-M, respectively, in order to determine the optimal dosage of PFA as an effective ASR suppressant for different RCG contents.

The ASR expansion results of the mortar bars prepared in Series V-M, VI-M and VII-M are shown in Figure 6.5.1, Figure 6.5.2 and Figure 6.5.3, respectively. The results indicate that 10% PFA by weight of total aggregate could effectively minimize the ASR expansion in the mortar bars prepared with 50% and 75% RCG. The mortar bars contained less than 25% RCG had little dimensional change even without the use of PFA after the 28-day test period.

Figure 6.5.4 shows the 28-day expansion of the mortar bars plotted against the RCG contents. The results show that the ASR expansion can be controlled to a safe limit if 10% by weight of total aggregate of PFA is added into the concrete mixture or the RCG content is limited to 25 % by weight of total aggregate or less.

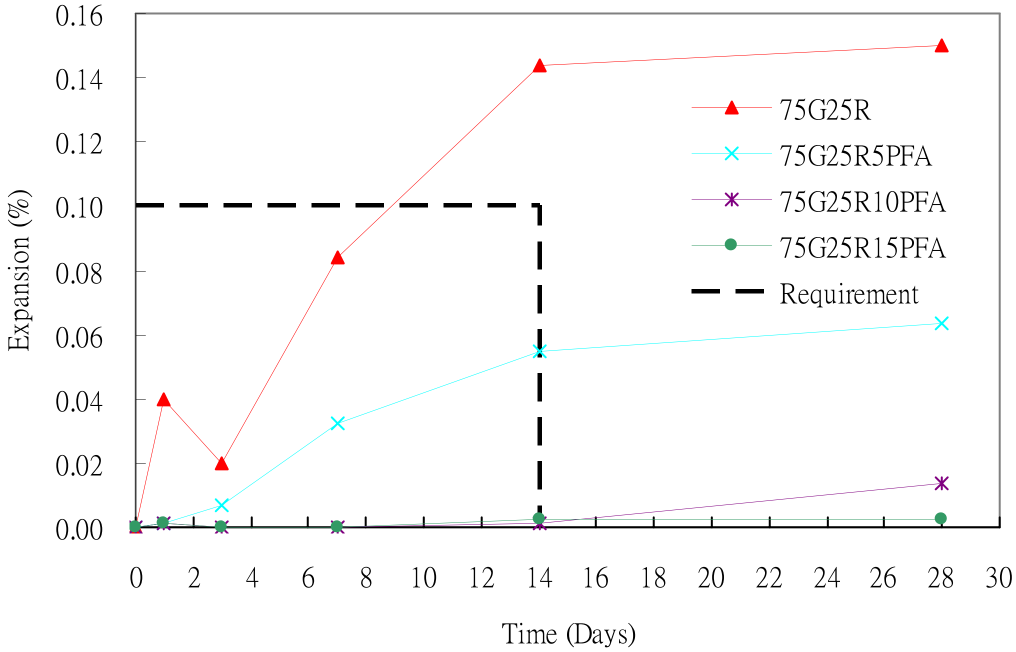


Figure 6.5.1 - Results of ASR expansion of mortar bars prepared in Series V

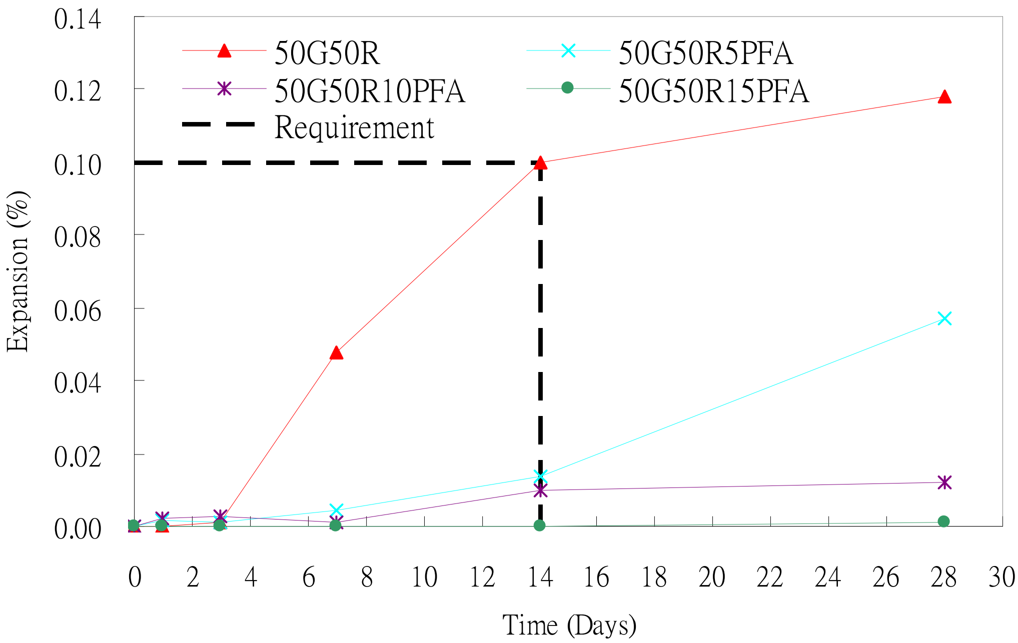


Figure 6.5.2 - Results of ASR expansion of mortar bars prepared in Series VI

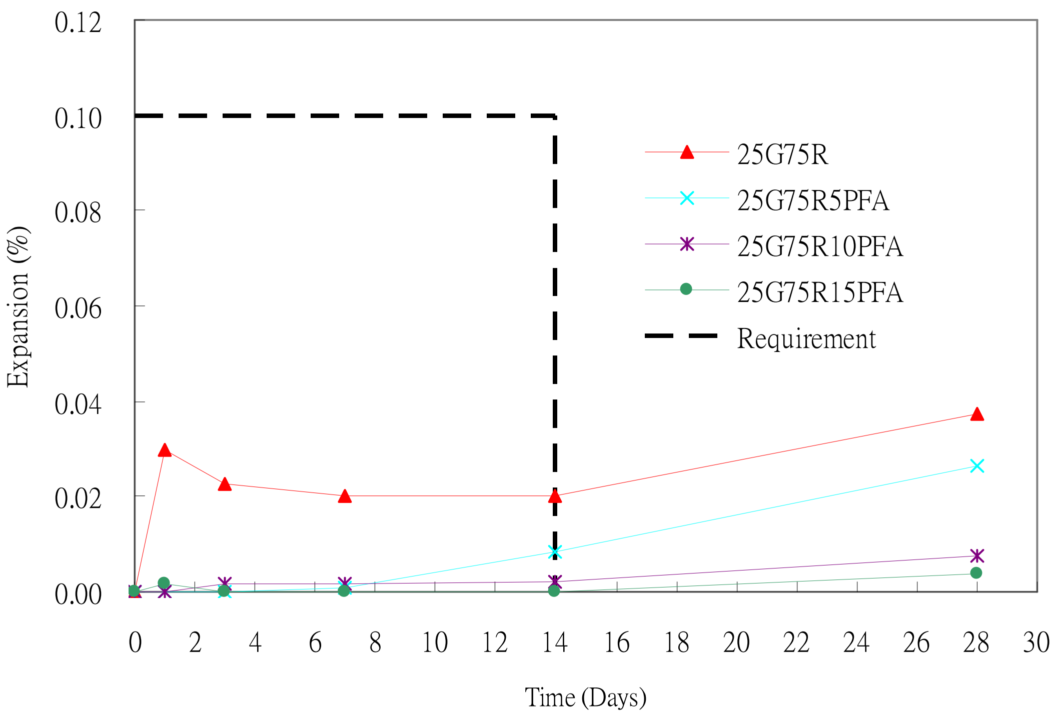


Figure 6.5.3 - Results of ASR expansion of mortar bars prepared in Series VII

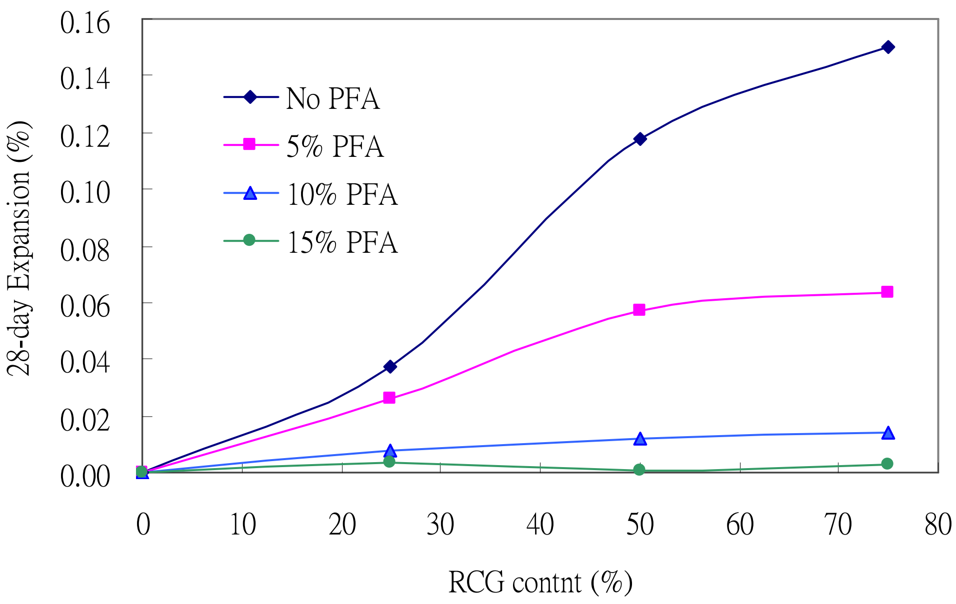


Figure 6.5.4 - Results of 28-day ASR expansion with different RCG content and PFA dosage

6.6 ASR expansion without PFA

Serious ASR expansion of mortar bars was observed when the glass content of the mortar bars that were prepared without the use of PFA was larger than 25%. It was also observed that the serious ASR expansion was accompanied with extensive cracking of the mortar bars (Figure 6.6.1). It is believed that the high glass content of the mortar bars would produce a substantial amount ASR reaction product on the surface of mortar bars and caused the serious cracking

Upon the cracking of the surface layer the NaOH solution would be able to penetrate into the mortar bars and further react with the glass cullet causing further expansion of the mortar bars. To prove this hypothesis, two mortar bars prepared with 75% and 25% glass contents respectively that had undergone the 28-day ASR test were selected for visual and SEM examinations. For the bar prepared with 75% glass cullet, some white particles/gel were found on the glass cullet (Figure 6.6.2) close to the cracks. The SEM photos of the white particles/gel are shown in Figures 6.6.3. to 6.6.6. On the contrary, for the bars prepared with 25% glass cullet, no white particles/gel was found (Figures 6.6.7). This was probably due to the expansive stress induced by the ASR reaction was not sufficient to introduce significant cracks on the surface of the mortar bars when the glass content was less than 25%.

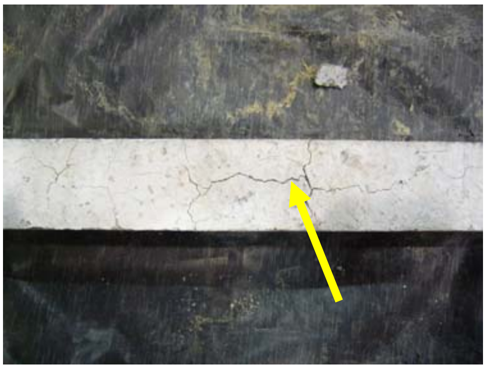


Figure 6.6.1. Extensive cracking on the surface of mortar bars.

Figure 6.6.2. White particles/gel on glass cullet

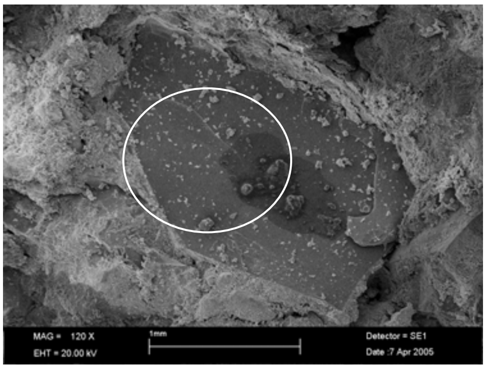


Figure 6.6.3. SEM 120x image of cracked glass showing white particles/gel

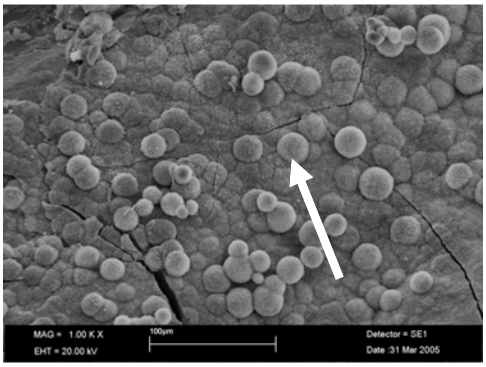
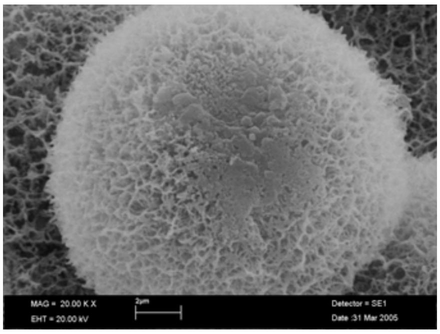


Figure 6.6.4. 1K X image of cracked glass and white particles/gel



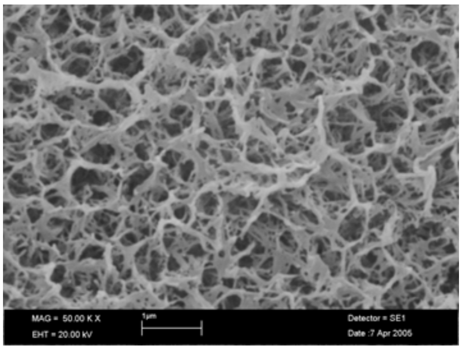


Figure 6.6.5. 20K X image of white particles/gel

Figure 6.6.6. 50K X image of white particles/gel

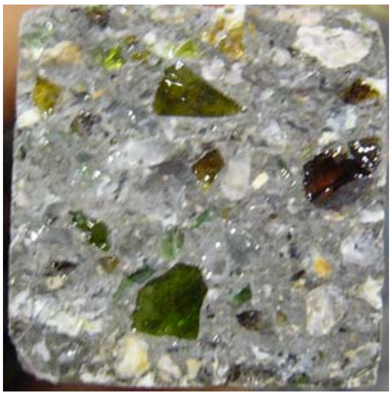


Figure 6.6.7. Cross section of the mortar bars (25% glass content)

6.7 ASR expansion with PFA

Previous studies showed that PFA was able to suppress ASR expansion. According to West [1996], one of the effects of adding PFA in concrete was to reduce permeability of the concrete. Hence, it is difficult for both water and alkali ions to go into the concrete. This would limit the extent of ASR.

Total porosity determination following a method described by Cheung [2005] was used to determine the pore and void contents of the mortar bars. The mortar bars with 75% glass content and different PFA contents were selected for the test. Figure 6.7.1 shows that the porosity was significantly reduced as the PFA content increased. To further illustrate the relationship between porosity and ASR expansion, the 28-day ASR expansion was plotted against the porosity of the mortar bars as shown in Figure 6.7.2. The expansion was increased as the porosity increased. PFA probably reduced the porosity of the mortar bars and blocked the NaOH solution from reaching the interior of the bars and therefore, no significant cracks were observed and the ASR expansion can be controlled.

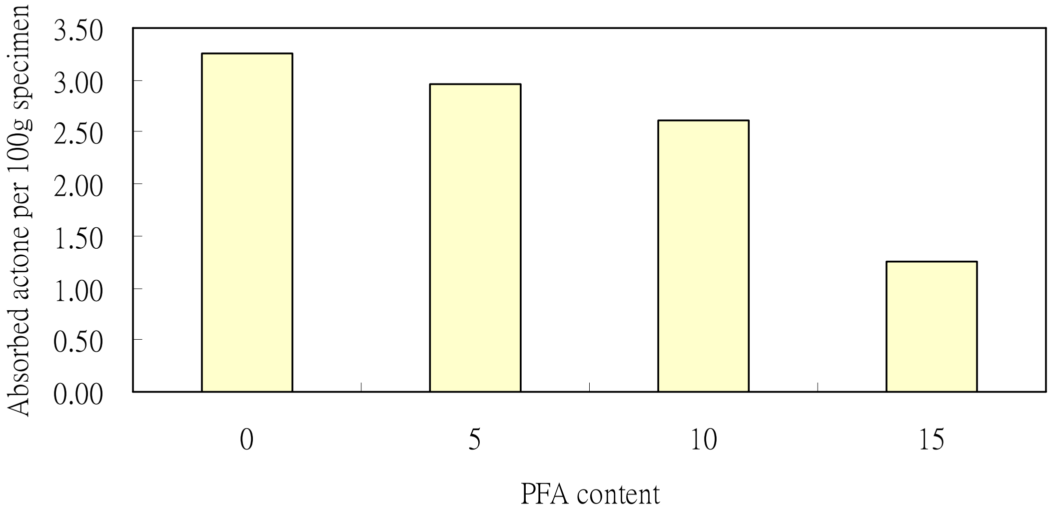


Figure 6.7.1 Relationship between the PFA content and porosity of the mortar bars.

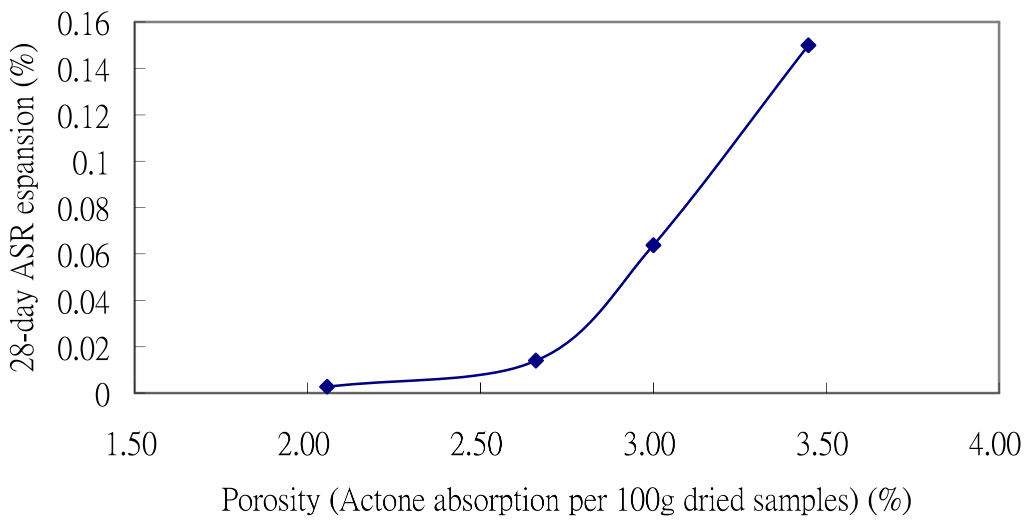


Figure 6.7.2 Relationship between the 28-day ASR expansion and porosity of the mortar bars.

6.8 Summary

In Chapter 6, the adequate amount of PFA as an ASR suppressant for mortar bars prepared with different RCG contents was investigated. The effects of adding PFA on the mortar bars were addressed. The following conclusions can be drawn:

1. It was not feasible to use 100% RCG without the use of mineral admixtures as ASR suppressant.
2. Both PFA and MK could suppress ASR expansion efficiently. However, PFA was a better choice due to its low material cost.
3. Negligible ASR expansion was induced when the mortar bars were prepared with 25 % RCG or less.
4. It is recommended that 10 % by weight of total aggregate of PFA was added into the concrete mixture to control the ASR expansion if the RCG content was 25 % or greater.

Chapter 7 The Properties of Concrete Blocks Prepared with Recycled Aggregate and Recycled Crushed Glass with Addition of PFA

7.1 Introduction

The result in Chapter 6 showed that the RCG was able to be used in concrete blocks when the glass content was less than 25%, by weight of total aggregates, or the PFA content was higher than 10%. Therefore, the effect of PFA on concrete blocks prepared with recycled aggregate and RCG was investigated in this Chapter. Concrete blocks were produced using the appropriate mix proportion (Table 3.2.4.1) derived in Chapter 6 of this study and the corresponding mechanical properties were measured. It was found that the incorporation of PFA caused a greater gain in strength from 28 days to 90 days compared to that of blocks without PFA. The skid resistance and density of the paving blocks reduced as the PFA content increased. However, the water absorption and abrasion resistance were not affected by the use of PFA.

7.2 The effect of PFA on the compressive strength of concrete block

Concrete blocks were prepared with different glass contents and PFA contents (Table 3.2.4.1) and their corresponding mechanical properties were measured. The test results are summarized in Table 7.2.1.

Table 7.2.1 – Test results of the paving blocks prepared in Series XI, XII and XIII

Notations	Density (kg/m^3)	Compressive strength (MPa)		Tensile splitting strength (MPa)	Abrasion resistance (mm)	Skid resistance (PBN)	Water absorption (%)
		28-day	90-day				
Series XI							
75G25R	2270	57.2	57.4	3.10	20	110	3.3
75G25R5P	2253	61.4	82.5	3.73	21	110	3.4
75G25R10P	2245	63.2	86.5	3.67	21	105	3.5
75G25R15P	2236	59.0	94.8	3.28	20	95	3.3
Series XII							
50G50R	2260	54.3	53.6	3.36	20	110	4.3
50G50R5P	2262	61.2	73.1	4.09	19	105	3.6
50G50R10P	2242	70.5	82.3	4.03	19	105	4.2
50G50R15P	2225	61.4	85.3	3.31	21	95	4.0
Series XIII							
25G75R	2275	56.6	60	3.90	21	110	4.7
25G75R5P	2235	60.5	73.1	3.31	20	110	3.9
25G75R10P	2220	62.4	70.2	4.02	19	105	4.5
25G75R15P	2207	61.3	74	3.94	20	95	4.6

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Figure 7.2.1 shows the compressive strength of the concrete blocks. The results indicate that the effect of the addition of PFA on 28-day strength was less significant compared to that of the 90-day strength which increased notably as the PFA content increased from 0% to 15 %. The strength gain from 28 days to 90 days of the concrete mixtures at different glass and PFA contents is shown in Figure 7.2.2, which shows that the gain in strength became more significant when the PFA content increased. The result could be attributed to pozzolanic reaction of the PFA particles at late test ages and the result was consistent with the previous study. However, it is worth to note that the compressive strength gain increased with increase in RCG content. According to a previous study [NYSERDA, 1997] , when the glass was ground to powder size (less than #400 sieve), the glass particles would have pozzolanic activities which could be the explanation of the higher gain in strength of concrete blocks prepared with the same PFA content but with a higher RCG content.

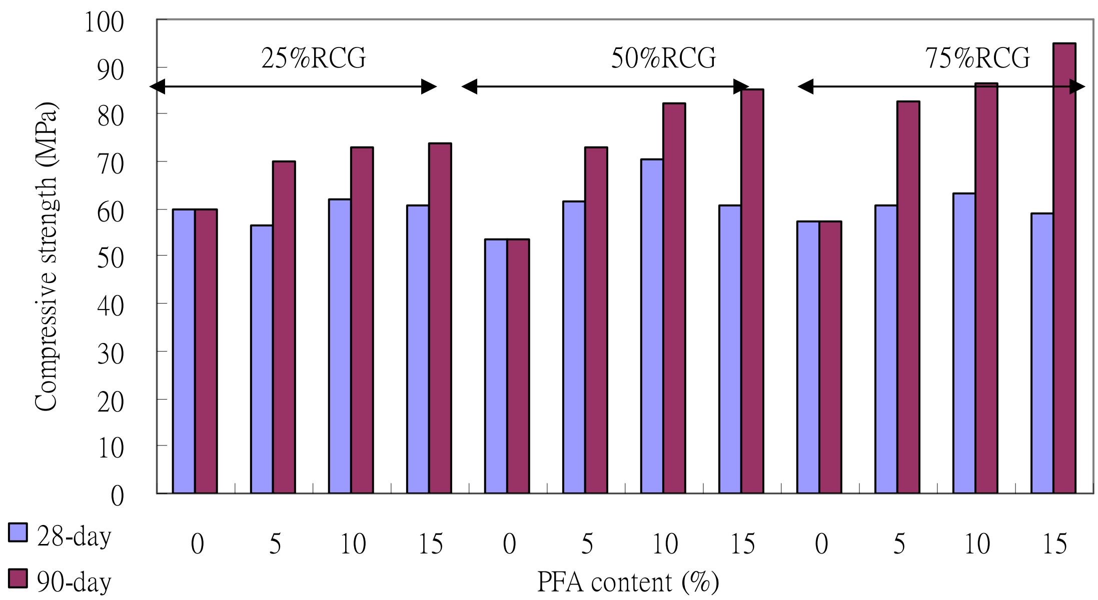

Figure 7.2.1 - Results of 28-day and 90-day compressive strengths of concrete paving blocks prepared with different glass and PFA contents.

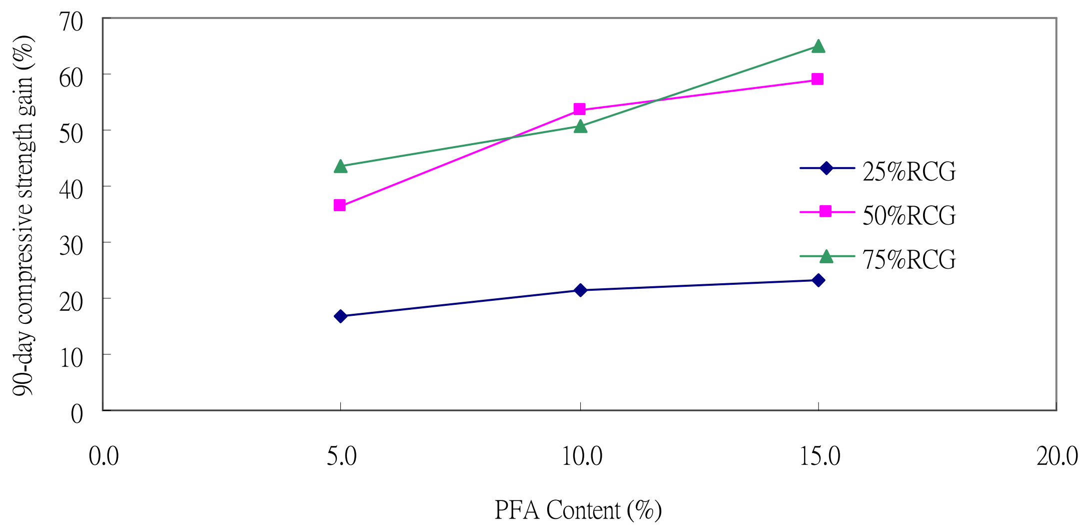

Figure 7.2.2 - Strength gain of concrete paving blocks prepared with different glass and PFA contents.

7.3 The effect of PFA on the skid resistance, abrasive resistance and water absorption of concrete block

Table.7.2.1 shows that an increase in the PFA content resulted in a lower skid resistance of the concrete blocks. Since the addition of PFA produced a more homogeneous mix which led to a smoother surface texture, thus reducing the skid resistance of the concrete blocks. However, it was found that the abrasion resistance was not affected by the PFA contents.

Figure 7.3.1 shows that the effect of the addition of PFA on the water absorption of the concrete blocks was less compared to that of the use of RCG. It is shown that the water absorption of the concrete blocks is strongly related to the water absorbability of the aggregate particles. Since RCG particles had a negligible water absorption value, it was of no surprise that the water absorption of the blocks decreased as the RCG content increased.

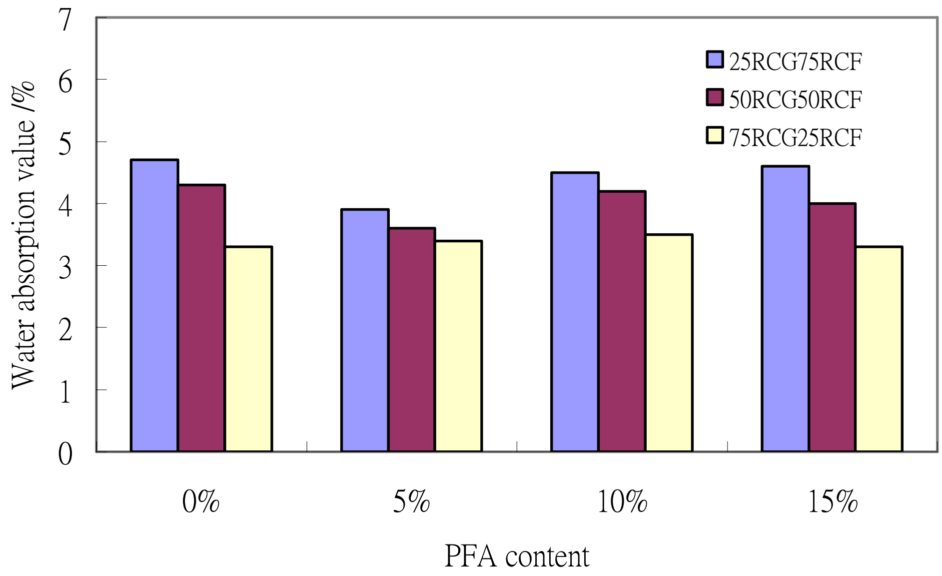

Figure 7.3.1 Results of water absorption of concrete paving blocks prepared with different glass and PFA contents.

Furthermore, it was found that the density of the blocks decreased as the PFA content increased (Figure 7.3.2). The comparison between the density of the aggregates, cement and PFA showed that PFA had the lowest density. Since the addition of PFA decreased the proportion of other ingredients in a unit volume, the density of the concrete blocks decreased accordingly after the addition of PFA.

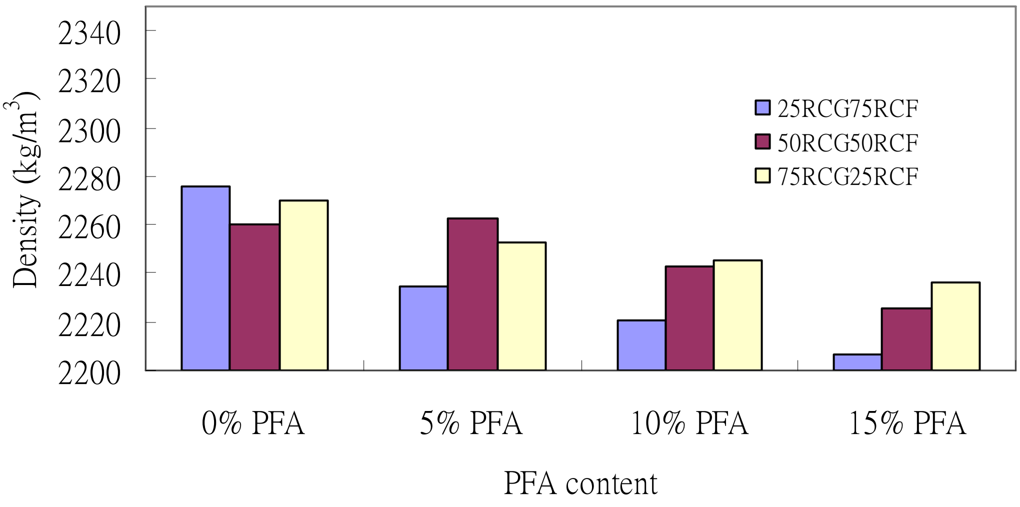

Figure 7.3.2 Results of density of concrete paving blocks prepared with different glass and PFA content.

7.4 Summary

In Chapter 7, the mechanical properties of concrete paving blocks prepared with RFA and RCG were measured. The effects of adding PFA on the mechanical properties of the concrete blocks were addressed. The following conclusions can be drawn:

1. The effect of PFA on the 28-day compressive strength was less significant compared to that of PFA on the 90-day strength.
2. At the same PFA content, the 90-day strength of concrete paving blocks increased with an increase in the RCG content.
3. The skid resistance and density reduced as the PFA content increased. However, the water absorption and abrasion resistance were not affected by the PFA content.
4. The water absorption of the paving blocks decreased as the RCG content increased.
5. An Eco-paving blocks using 100% waste materials as aggregates could be produced by using 50 % RCG and 50 % RFA with an addition of 10 % by weight of total aggregate of PFA.

Chapter 8 Industrial Production of Concrete Blocks

8.1 Introduction

With the assistance of a local block manufacturer, a number of plant trials were conducted. But due to the availability of plant time, only two series of paving blocks were produced. The mix proportions used in the plant trials are given in Tables 8.2.1 and 8.2.2.

8.2 Test Results

The compressive strength of the factory produced blocks are compared with the laboratory produced blocks in Figure 8.2.1. Generally, for the same A/C ratios, the laboratory produced blocks achieved higher strength. This can be attributed to the difference in compaction applied as noticed in the density results (Figure 8.2.2). Nevertheless, the general trend of the factory produced blocks shows that the strength decreased with increasing A/C ratios and is consistent with the results of the laboratory study. The results also demonstrate that for an A/C ratio of 3, the blocks that were produced by the blending natural and recycled aggregates with a FM value lying between 3.6 and 3.8 had higher compressive strength values. This is consistent with the findings of Chapter 5.

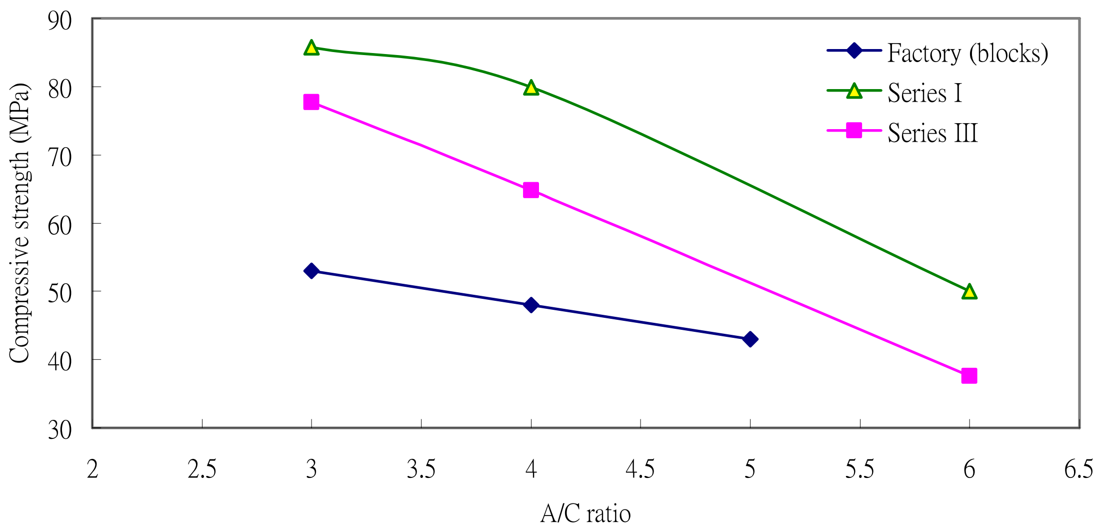

Figure 8.2.1 Relationship between compressive strength and A/C ratio

Table 8.2.1 Test results of 80mm concrete paving blocks

	Compressive strength (MPa)	Water absorption	A/C ratio	Recycled aggregate (%)	Natural aggregate (%)	FM value
P-1	43	7.2	5	80	20	3.5
P-2	48	6.5	4	80	20	3.5
P-3	53	5.3	3	80	20	3.5

Table 8.2.2 Test results of 60mm concrete paving blocks

	Compressive strength (MPa)	Water absorption	A/C ratio	Recycled aggregate (%)	Natural aggregate (%)	FM value
P-4	45	3.5	3	70	30	3.7
P-5	46	3.4	3	70	30	3.8
P-6	42	3.3	3	45	55	3.4
P-7	46	3.8	3	40	60	3.6
P-8	46	3.7	3	35	65	3.8
P-9	47	3.1	3	60	40	3.6
P-10	43	5.3	3	50	50	3.4

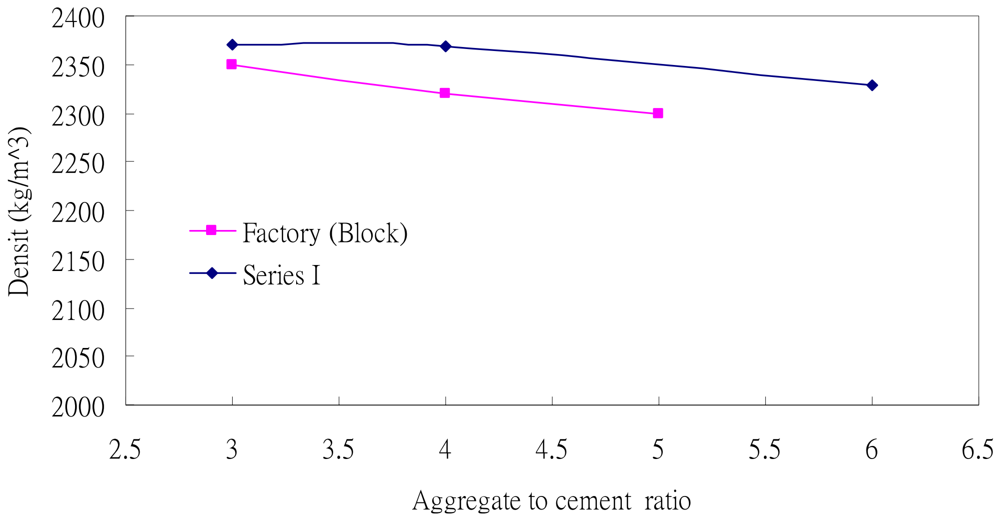

Figure 8.2.2 Relationship between density and A/C ratio

Besides, a block making machine supplier in China gave an optimal mix proportion for 40 and 60MPa concrete paving block shown below:

Table 8.2.3 Optimum mix proportions from a China block making machine supplier

Strength	Cement	Sand	Coarse aggregate	A/C ratio	FM value
40MPa	1	2.12	2.38	4.5	3.9
60MPa	1	1.65	1.85	3.5	3.9

The recommended mix proportion indicated the importance of A/C ratio and the suitability of aggregate grading (FM=3.9).

8.3 Recommended mix proportions

Based on the above findings, the following recommendations are made:

Suggested A/C ratio : 3 for grade 45, and 4.5 for grade 30 blocks

FM value of aggregates: 3.5 to 4.5.

Content of recycled aggregates: max. 50% of total aggregates (for type A); and max 75% (for type B).

Content of the recycled crushed glass: max. 50% of total aggregates

PFA content : 10% by weight of total aggregates if recycled crushed glass is used.

Chapter 9 Conclusion and recommendations for further

9.1 Conclusions

The conclusions of the study are summarized below:

1) The compressive strength of concrete blocks increased with a decrease in A/C ratio.
2) The compressive strength was directly proportional to strength of the blended aggregate.
3) The water absorption of the blocks was closely related to the water absorbability of the aggregate particles.
4) The water absorption of the paving blocks decreased as the RCG content increased.
5) It was not feasible to use 100% RCG without the use of mineral admixtures as ASR suppressant.
6) Negligible ASR expansion was induced when the mortar bars were prepared with 25 % RCG or less.
7) At the same PFA content, the 90-day strength of concrete paving blocks increased with an increase in the RCG content.
8) The results in Chapter 6 showed that aggregates with the FM value ranging from 3.5 to 4.5 was most suitable for concrete block production where the compressive strength, water absorption and abrasion resistance were the optimum.
9) The compressive strength, abrasion resistance and water absorption improved as the

packing density increased. It was also found that a better surface texture of concrete block was obtained when the packing density of the aggregate was larger than 0.7.

10) To optimize the properties of concrete block production, the grading of the blended aggregates used should be similar to the ideal grading curve proposed. Alternatively, the FM and packing density of the blended aggregate should range from 3.5 to 4.5 and be larger than 0.7.

11) Both PFA and MK could suppress ASR expansion efficiently. However, PFA was a better choice due to its low material cost.

12) It is recommended that 10 % by weight of total aggregate of PFA was added into the concrete mixture to control the ASR expansion if the RCG content was 25 % or greater.

13) The effect of PFA on the 28-day compressive strength was less significant compared to that of PFA on the 90-day strength.

14) To make use of recycled materials to produce eco-friendly (100% recycled materials as aggregates) paving blocks with good quality, it is recommended to prepare the blocks with 50% recycled crushed glass (RCG) and 50% recycled fine aggregate (RFA) and with an A/C ratio 4 or below. An addition of 10% PFA was also recommended in the mixtures in order to resist ASR expansion and have better mechanical properties.

9.2 Recommendations for further research

The following further work is recommended:

1) A larger scale trial production using the recommended mix proportions should be carried out.
2) The influence of the glass particle size on the ASR should be further studied.
3) The influence of the glass colors on the ASR should be further studied.

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